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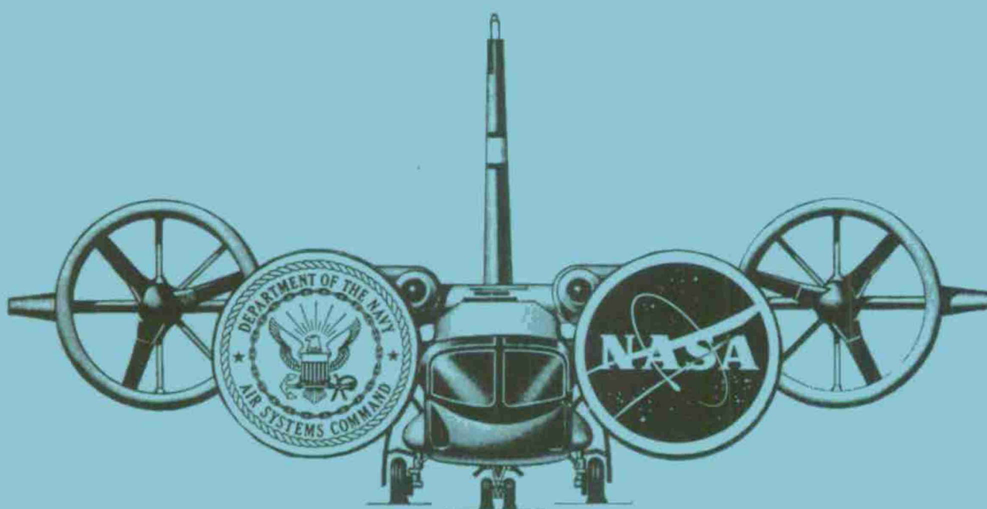
A FLIGHT INVESTIGATION OF CONTROL, DISPLAY, AND GUIDANCE REQUIREMENTS FOR DECELERATING DESCENDING VTOL INSTRUMENT TRANSITIONS USING THE X-22A VARIABLE STABILITY AIRCRAFT

VOLUME I: TECHNICAL DISCUSSION AND RESULTS

Final Report

September 1975

by
J. V. Lebacqz
E. W. Aiken



Prepared Under Contract N00019-73-C-0504

For

Naval Air Systems Command
Department of the Navy

By

Calspan Corporation
Buffalo, New York

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FOREWORD

This report was prepared for the United States Naval Air Systems Command under Contract Number N00019-73-C-0504 by Calspan Corporation (formerly Cornell Aeronautical Laboratory, Inc.), Buffalo, New York, and documents the research program performed under that contract during the period May 1973 to September 1975.

The flying qualities experiment reported herein was performed by the Flight Research Department of Calspan. Mr. J. L. Beilman was the Program Manager. Mr. J. V. Lebacqz was the Project Engineer, and Mr. E. W. Aiken was the research engineer; Mr. R. D. Till was the project engineer for the electronic systems, both airborne and ground-based. Technical monitoring was performed by both the Naval Air Systems Command and the National Aeronautics and Space Administration Langley Research Center; the authors wish to acknowledge their appreciation to Messrs. L. V. Schmidt, R. Siewert, F. Pierce, and J. Raggetts of NASC, and to Messrs. R. J. Tapscott, J. Garren, F. R. Niessen, R. Yenni, and L. Person of NASA-LRC. The authors also acknowledge their appreciation to Messrs. R. Noury, M. Underwood, and J. Day of the Bell Aerospace Company for their assistance in the operation of the AN/SPN-42T1 tracking radar system used during the experiment.

Research programs using the X-22A aircraft require extensive efforts and contributions from a large number of individuals at Calspan. The authors are particularly grateful to: Mr. N.L. Infanti, Calspan Chief Pilot who was the safety pilot, and Mr. G.W. Hall, evaluation pilot, for their efforts in the conduct of the flights under frequently trying circumstances; Mr. R.D. Till and Mr. T.J. Gavin, who were responsible for the design and fabrication of the airborne analog computer and display symbol generator; Dr. R.T.N. Chen, who was responsible for the design of the decoupled velocity control system and whose technical insight was invaluable; and Mr. J.L. Lyons, who was responsible for the extensive data processing and reduction required on this program. In addition, the contributions of Mr. R.E. Smith, who was project engineer for the first three months of the program, and Mr. C.R. Chalk, Head, Aeronautical Engineering Branch, were significant during various phases of the experiment design. The authors are also grateful for the outstanding efforts of the individuals responsible for mechanical maintenance (Messrs. D. Dobmeier, H. Chmura, G. Ewers, R. Solo, W. Wilcox) and electrical fabrication and maintenance (Messrs. J. Wilson, J. Shattuck, T. Franclemont, C. Bulgey) of the X-22A systems. Finally, special thanks are given to Mses. F. Scribner, M. Ford, D. Kantorski, and J. Cornell for their assistance in the preparation of this report.

ABSTRACT

The third flight research program using the variable stability X-22A aircraft was undertaken to investigate control, display, and guidance requirements for VTOL instrument transitions. The primary purpose of the experiment was to provide meaningful data related to the interaction of aircraft control system and displayed information characteristics on pilot rating and performance during a steep decelerating descending transition from a representative forward velocity (100 Kt) to the hover completely under instrument conditions. Thirty-eight in-flight evaluations were performed of combinations of five generic display presentations, ranging from position-information-only to four-axis control directors, and five levels of control augmentation systems, ranging from rate-augmentation-only to decoupled longitudinal and vertical velocity responses and automatic configuration changes. In addition, new guidance developments of fundamental importance to VTOL instrument terminal area operations, including an Independent Thrust Vector Inclination Command (ITVIC) and a procedure for automatically switching between airspeed and ground speed tracking to account for headwinds and crosswinds, were conceived, designed, and demonstrated during the experiment. Primary results of the program include the demonstration of an inverse relationship between control complexity and display sophistication, as was hypothesized in the experiment design, and the definition of acceptable and satisfactory control/display combinations. In particular, it was found that the explicit display of translational velocities is required for a satisfactory system, regardless of control system complexity or automation, and that rate-augmentation-only may be acceptable (though still unsatisfactory) only if full control director commands are provided in addition to velocity status information. Analysis of the results in terms of simple pilot-in-the-loop considerations and measured performance and workload provide initial guidelines for the design of future VTOL control-display characteristics.

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Section I

INTRODUCTION AND SUMMARY

1.1 INTRODUCTION

The development of an instrument landing capability for V/STOL aircraft is a prerequisite for the extension of VTOL operations into restricted areas in all weather conditions. To provide this capability, problems must be solved which are more difficult than the corresponding problems for CTOL aircraft, because the landing approach now involves not only control of the spatial position of the aircraft but also precise control of a non-constant total velocity; this task requires active use of at least one additional controller, and furthermore requires additional information to the pilot concerning the increased dimensions of his task. The pilot's control problem is exacerbated by the generally degraded flying qualities encountered as the dependence on powered lift increases, and, in VTOL configurations different than the helicopter, by an additional control requirement related to the conversion from forward flight to powered lift (e.g. wing tilt, rotor tilt, jet thrust vectoring).

It is clear, therefore, that studies of the VTOL instrument landing approach problem must consider both the definition of required levels of information presentation for the pilot and the determination of required degrees of stability and/or control augmentation for the aircraft. An excellent summary of this problem and recommendations for future research are given in the AGARD Advisory Report on V/STOL display requirements for landing (Reference 1). In this discussion of necessary research, the AGARD Working Group placed a high priority on determining the interplay between display and control complexities. This interplay is schematically illustrated in Figure 1-1, taken from Reference 1. The hypothesis is that an inverse relationship exists for a given pilot rating level between control complexity and display sophistication; the problem is to quantify to some extent these two axes and attempt thereby to define satisfactory or adequate combinations.

The primary purpose of the flight experiment described in this report was therefore to provide meaningful data related to the interaction of aircraft control system and pilot display characteristics on pilot rating and performance during the conduct of representative VTOL terminal area operations under instrument conditions. To achieve this objective within the constraints of a relatively limited program scope (approximately 45 flight hours including set-up and calibration), the major variables selected for investigation were the type of stability/control augmentation system and the level of displayed information; potential experimental variables, such as evaluation task or guidance command relationships, were designed and verified during extensive ground simulations and held fixed for the flight experiment. The general framework of the investigation was based on expanding results of previous experimental investigations -- which in general considered only one control system type and/or one display presentation format -- by exploiting the variable stability capability of the X-22A V/STOL research aircraft (Figure 1-2) to examine more

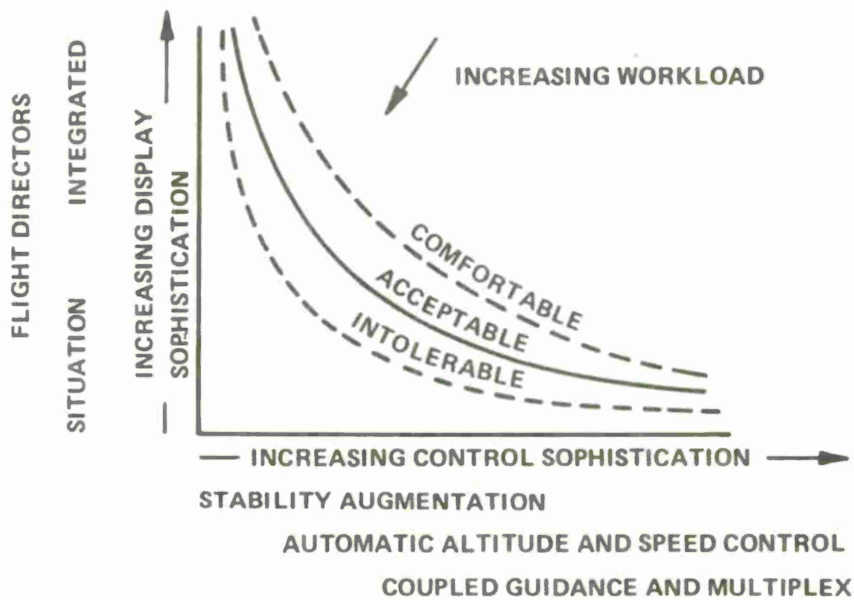


Figure 1-1 TRADE OFF BETWEEN DISPLAY AND CONTROL SOPHISTICATION (FROM REFERENCE 1)

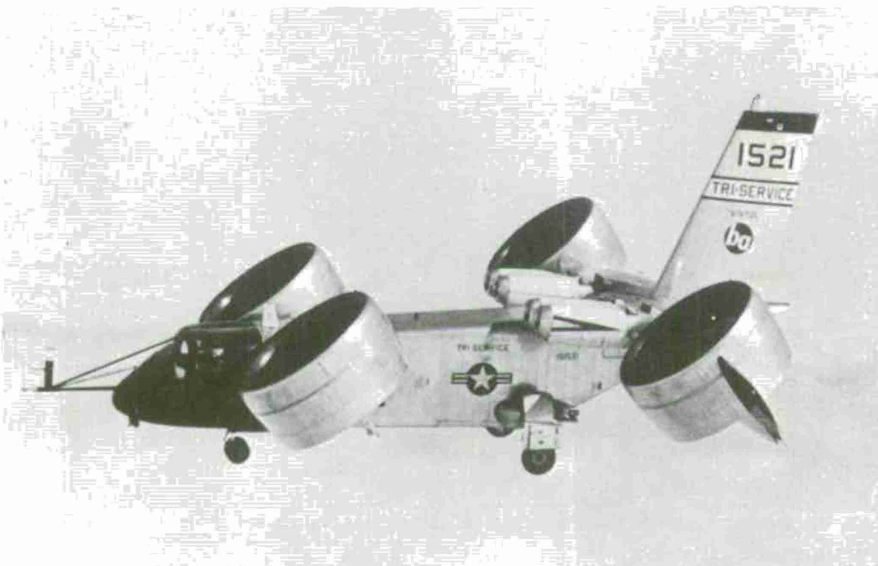


Figure 1-2 X-22A VARIABLE STABILITY V/STOL AIRCRAFT

than one type of stability/control augmentation system, and by constructing a programmable symbol generator to provide a variable format on an electronic CRT display.

To provide a review of this research program for readers who wish to gain an overall understanding of the experiment from a qualitative standpoint, the following subsection gives a brief summary of the major elements, results, and conclusions; References 2 and 3 are recommended as expanded summaries. Section 1.3 provides an outline of and guide to the remainder of this report for those readers who are interested in a more complete description of the program.

1.2 SUMMARY OF THE RESEARCH EXPERIMENT

Five types of control augmentation schemes were examined as one of the two major variables in the experiment and may be summarized as:

- Rate augmentation: pitch rate feedback
  roll rate feedback
  yaw rate feedback
  manual duct rotation
  unaugmented vertical axis

- Attitude/Rate: command: pitch attitude command
  roll rate-command-attitude-hold
  dual mode directional (turn following or heading hold)
  manual duct rotation
  unaugmented vertical axis

- Attitude command: pitch attitude command
  roll attitude command
  dual mode directional
  manual duct rotation
  unaugmented vertical axis

- Automatic λ : pitch attitude command
  roll attitude command
  dual mode directional
  automatic duct rotation
  unaugmented vertical axis

- Decoupled velocity: decoupled, augmented longitudinal velocity control
  roll attitude command
  dual mode directional
  automatic duct rotation
  decoupled, augmented vertical velocity control

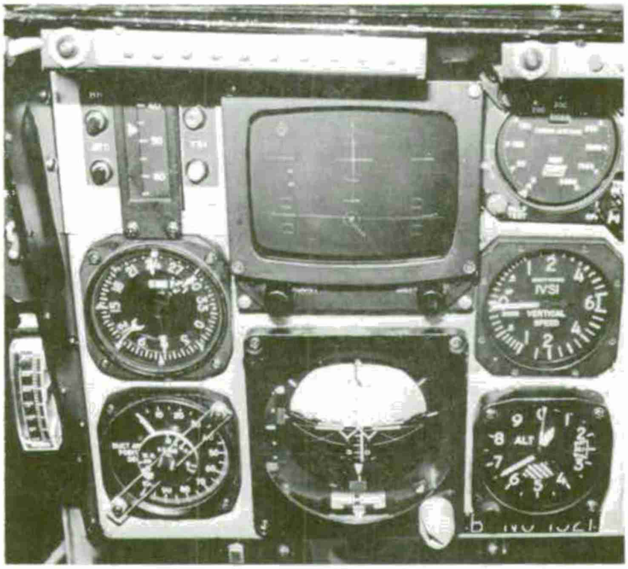
The intent during the design of the augmentation systems was to examine generic levels of complexity to aid the design of future augmentation schemes, and so the dynamic characteristics of each were chosen to be "good" in the sense of compliance with MIL-F-83300 (Reference 4) when possible. In order to ensure continuity with previous experimental work, the concept and characteristics of the baseline attitude command system were chosen to be similar to those implemented in the VALT program done at NASA-Langley (Reference 5); the less complex and more complex systems were designed consistent with past design practice and projected possibilities.

A schematic diagram of the evaluation pilot's instrument panel is given in Figure 1-3. The primary instrument was an electronic CRT which presented integrated vertical and horizontal information in formats which could be varied during flight; major auxiliary information consisted of a radar altimeter with both analog and digital readout, a LORAS longitudinal airspeed tape instrument, a light for configuration change director information, a conventional electromechanical ADI including three-axis flight director elements, a duct angle instrument and conventional RMI, IVSI, and barometric altimeter instruments.

The major display variable in this experiment was the electronic display (ED) format. The intent of the variation in the electronic display format was to present the pilot three generic levels of displayed information. They were:

- ED-1: position and commanded position
- ED-2: position, commanded position, vertical and horizontal velocity and commanded velocity information
- ED-3: position, commanded position, horizontal-plane velocity, with longitudinal, lateral, and collective stick control director information.

Two variations on these basic formats were also investigated. Format ED-2+ presented collective stick control director information in lieu of vertical velocity error information, and was included because of the high pilot workload associated with the vertical axis. Format ED-1/FD consisted of the ED-1 electronic display and three-axis control director information displayed on the electromechanical ADI; this display configuration was included to reproduce the format used in the NASA-Langley VALT program (Reference 5) and to confirm the requirement for integrated displays. In addition, a thrust inclination director which provided a separate command for the required configuration changes (duct rotation) was conceived and investigated as an additional display element. The electronic display formats are summarized in Figure 1-4.



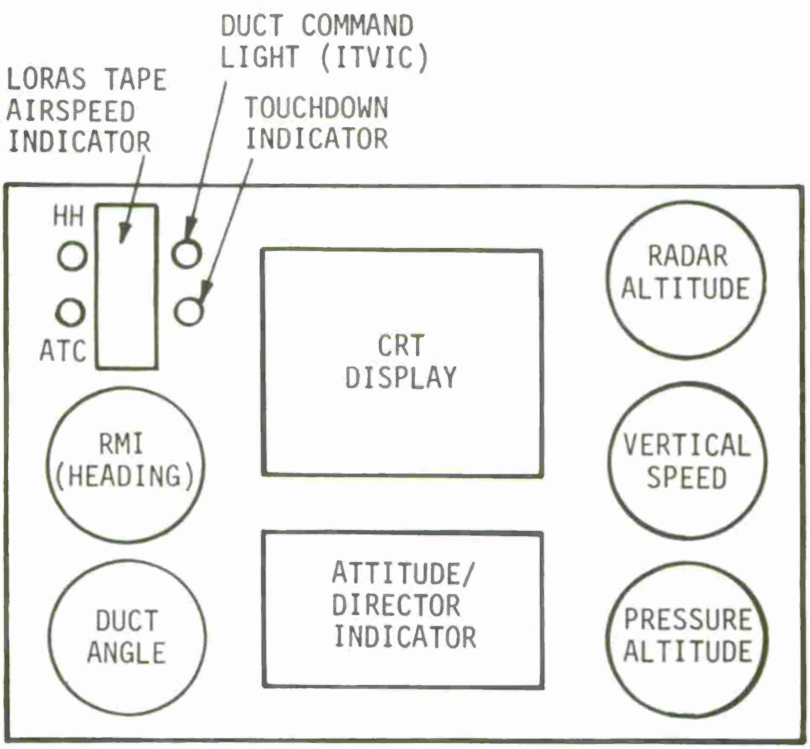
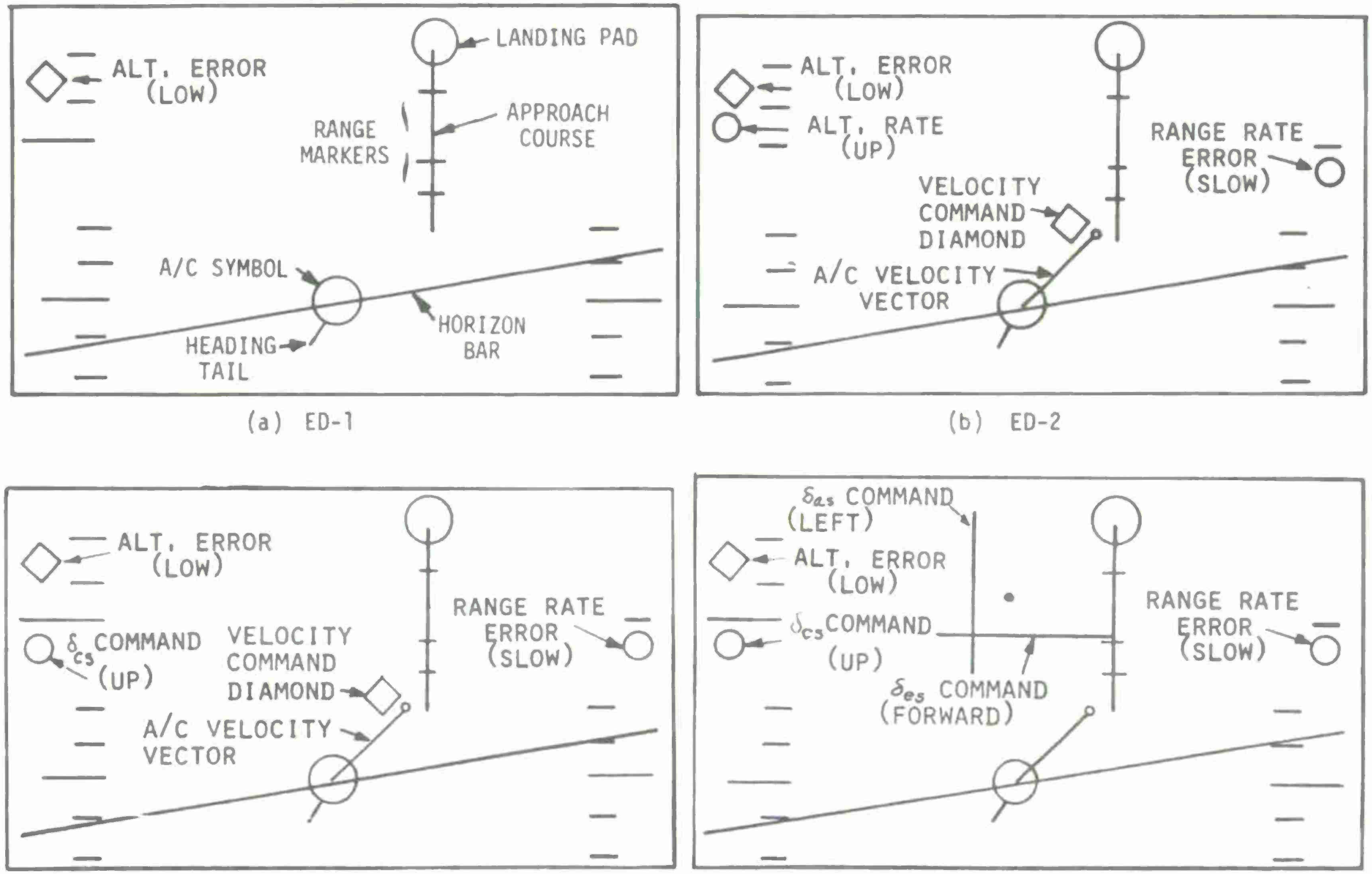


Figure 1-3 EVALUATION PILOT INSTRUMENT PANEL



(a) ED-1

(b) ED-2

(c) ED-2+

(d) ED-3

Figure 1-4 ELECTRONIC DISPLAY FORMATS

To provide the status and command information required for presentation on the displays, raw X, Y, Z data telemetered to the aircraft from a tracking radar were processed entirely onboard the aircraft with an analog computer. This processing consisted initially of obtaining smoothed values for translational rates and positions by blending the radar data with onboard linear accelerometer outputs through complementary filters; this status information was then used to provide commands for:

- Longitudinal velocity as a function of range (deceleration profile)
- Lateral velocity as a function of lateral position
- Aircraft configuration change as a function of command velocity
- Vertical position as a function of range (glide slope)
- Vertical velocity as a function of range

As will be discussed later in this report, two unique features of the command laws were conceived and developed for this experiment. First, the longitudinal and lateral velocity commands automatically switched between commanding: (1) airspeed and aircraft heading during localizer and glide slope acquisition, and (2) ground speed components parallel and perpendicular to the desired course during deceleration and hover. This logic was designed to account for along-track and cross-track wind components, and is necessary for the VTOL application in which wind speed and aircraft speed become of the same magnitude near the hover. Second, an Independent Thrust Vector Inclination Command (ITVIC), or configuration change command, was implemented to provide duct rotation commands to the pilot during the deceleration.

Combinations of the five levels of display sophistication and the five control augmentation systems discussed earlier formed the configuration matrix for the flight experiment. The pilot's evaluation tasks for each configuration consisted of two fully hooded instrument approaches, starting in level flight at 1700 ft AGL with an airspeed of 100 KIAS and duct angle of 15°, and ending at 100 ft AGL, zero groundspeed, and duct angle of approximately 90°. The elements of each approach are shown in Figure 1-5 and summarized below:

- level flight localizer acquisition (1700 ft AGL, 100 Kt)
- constant speed (100 kt) glide slope acquisition (7.5 degrees) at approximately 12,000 ft range
- constant deceleration (.05g) on the glide slope, commencing at a range dependent on headwind (zero-wind range approximately 8000 ft)

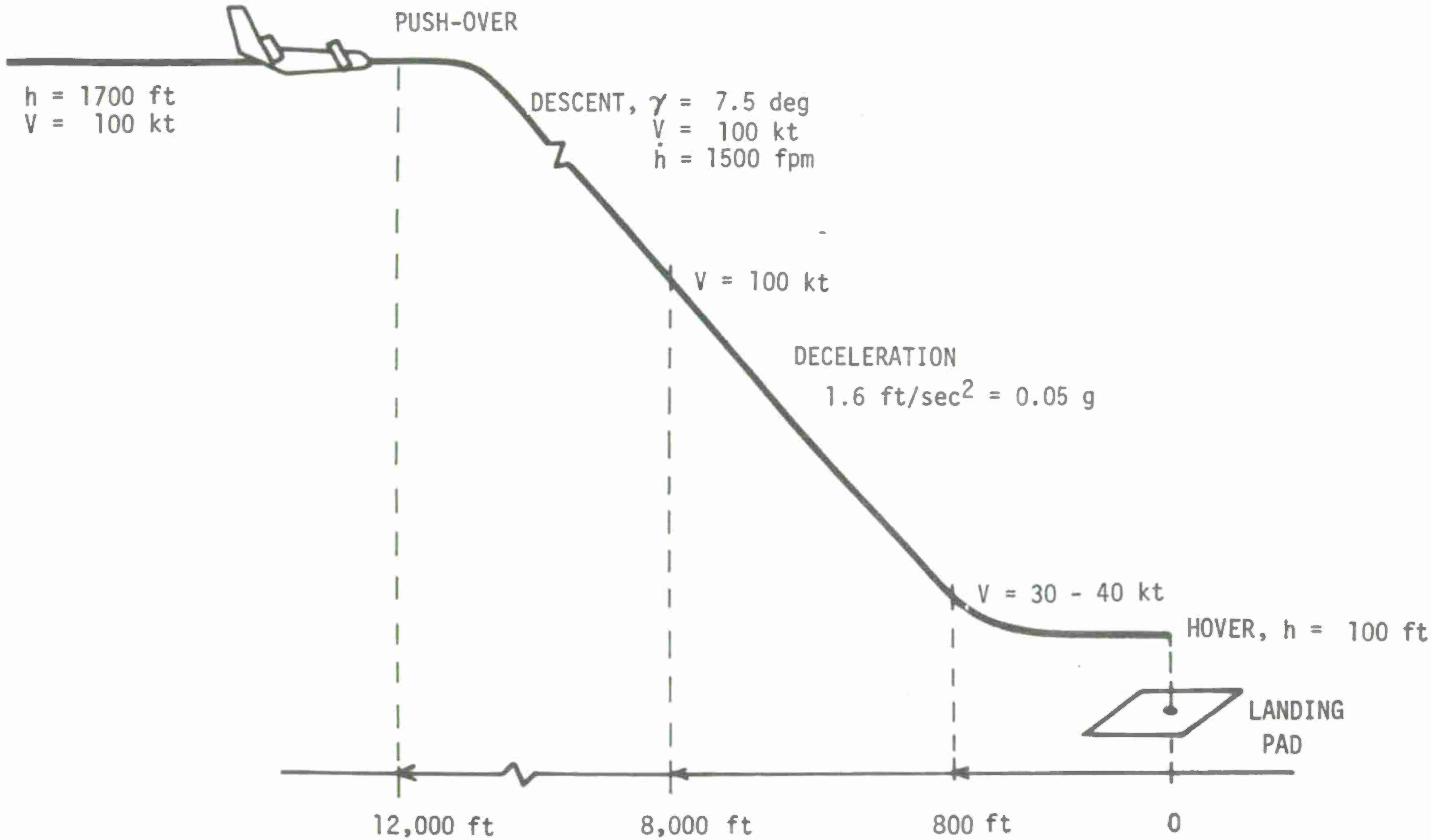


Figure 1-5 EVALUATION TASK

- flare to level final approach altitude of 100 ft commencing at approximately 1000 ft range, deceleration continuing to hover.

- hover at 100 ft above simulated pad, vertical airwork as desired.

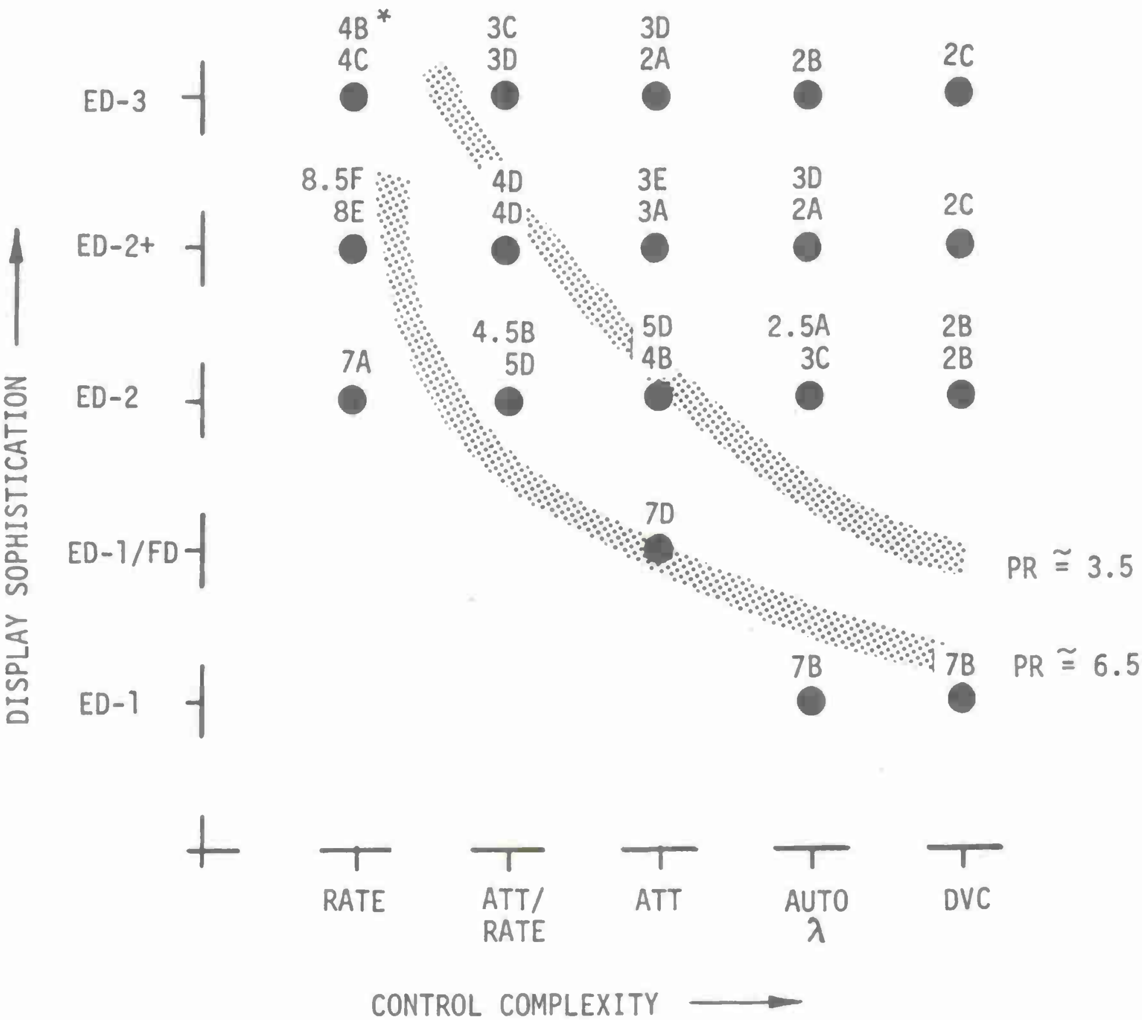
At the conclusion of the second approach, the pilot made comments with reference to a detailed comment card, on the aircraft response and display characteristics, and then assigned a Cooper-Harper pilot rating (Reference 6) and turbulence effect rating to the configuration. Thirty-eight evaluations of 21 control-display configurations were obtained during the course of the experiment by one evaluation pilot; additional data include measured tracking performance errors, workload indices, and aircraft response calibration records.

The bulk of the pilot rating data obtained is summarized in Figure 1-6 on a "plot" of display sophistication versus control complexity. This presentation of the results is chosen to facilitate comparison with the AGARD figure shown in Figure 1-1; it is emphasized that the axes are ordinal rather than interval, and that the approximate iso-rating lines refer only to the data specifically on the figure. In a general sense, the most apparent result is the demonstration of the hypothesized interaction between control complexity and display sophistication, particularly for a satisfactory rating ($PR \leq 3.5$): as the level of augmentation and/or automation increases, the required display presentation decreases from full integrated control director information (ED-3) to velocity and velocity command information both horizontally and vertically (ED-2). It is also apparent that, for a combination to receive a satisfactory rating, the display must explicitly include velocity status information. This requirement is primarily hover-oriented, and is a function of the need to know translational drift velocities accurately for precision station-keeping or touchdown; it is worth noting that, although fully-hooded landings were not considered as part of the evaluation task, a few such "blind" landings were actually performed during the course of the experiment. A final general result can be observed by noting that, as long as velocity is explicitly shown, no trend of pilot rating with display sophistication was found for the decoupled velocity control system: if "good" aircraft response characteristics relative to the required task are provided, the details of the displayed information become less important to satisfactory system performance.

Several specific results that relate to previous experimental work are:

- Pilot comments indicate a preference for attitude command in both pitch and roll for precision instrument hover.

- Pitch and roll control directors are not required for a satisfactory system if attitude command control systems with good dynamic characteristics in pitch and roll are provided.



*Numbers are Cooper-Harper pilot ratings, letters are turbulence effect ratings. Two ratings indicates two separate evaluations of a configuration.

Figure 1-6 PILOT RATING DATA FOR PRIMARY MATRIX (NO CROSSWINDS, WITH ITVIC)

- Pitch and roll control directors are required for an adequate system if rate augmentation only is provided.

- A configuration change director (ITVIC) is required for a satisfactory system when configuration changes must be performed manually.

A detailed discussion of all the pilot rating results, as well as of the implications of measured performance and workload indices, is contained in the body of this report.

General conclusions which may be drawn from the results of this flight program are:

- Descending decelerating approach transitions from forward flight to the hover may be performed by VTOL aircraft under instrument conditions given satisfactory control and display system characteristics as defined by this experiment.

- A tradeoff between control augmentation complexity and display presentation sophistication exists for generic levels of each.

- Precision hover under instrument conditions requires explicit display of translational velocity for a satisfactory system.

Again, more specific conclusions are discussed in the body of this report.

1.3 GUIDE TO THE REPORT

The general arrangement of this report is in two volumes. This volume contains a detailed discussion of the design, conduct, and results of the experiment; Volume II consists of appendices containing supportive data. The remainder of Volume I may be considered as being in two parts which are complementary but are oriented toward readers with differing interests. The first part (Sections 2 through 6) provides a comprehensive review of the design of the experiment, and is intended to provide the interested reader with a broad understanding of the reasons for the final design details. For readers who prefer to concentrate on the actual experiment, these sections may be skipped for the second part (Sections 7 through 12), which describes the evaluations and results. An outline of the contents of each section is given below.

Section	Information
2.0	Applicable previous theoretical and experimental research related to VTOL landing approach problem and control-display requirements.
3.0	Reasons for selected approach trajectory, relevance to civilian/military V/STOL applications.
4.0	Definition of guidance in context of experiment, estimation of spatial position and velocity, generation of horizontal and vertical plane commands, definition of airspeed/ground speed switching logic, configuration change command.
5.0	Selection of control system types, individual system characteristics, comparison with military flying qualities requirements.
6.0	Review of display design principles, rationale for format selection, sensitivities and scalings, control director design, evolution of final system.
7.0	Rationale for selected control-display combinations, definition of matrix.
8.0	Equipment summary, evaluation task and procedure, simulation situation, data acquired.
9.0	Analysis of Cooper-Harper pilot rating data, interpretation of pilot comments.
10.0	Summary of performance and workload analyses, performance/workload effects on pilot rating.
11.0	Conclusions from experiment.
12.0	Applicability of results to other VTOL aircraft, recommendations for further research.

Section II

BACKGROUND

2.1 SYNOPSIS OF SECTION

The purpose of this section is to review the context within which this experiment was designed. First, the genesis of the program goal will be discussed and the objectives of the experiment will be defined. Then, in order to place the design in perspective, the most relevant studies which had been performed prior to this program will be reviewed. The emphasis of the review will be on experimental and analytic programs which considered the VTOL landing approach problem from the complete pilot-display-aircraft system point of view and which had a direct bearing on the design of this experiment; applicable previous research that is specific to particular aspects of the problem, such as control system or display design theories, will be reviewed as required in the applicable sections of this report. Finally, on the basis of this review, the many interrelated factors which were possibilities for investigation are outlined, and the procedure by which the experimental variables were selected from these possibilities is summarized.

2.2 EXPERIMENT OBJECTIVES

It is clear that the capability of V/STOL aircraft to operate into restricted areas can provide significant advantages for both commercial and military users, and in fact these advantages have been demonstrated under visual flight conditions. The extension of this capability under instrument conditions, however, has proved to be much more difficult than the same extension for CTOL aircraft, because for VTOL aircraft, the landing approach requires precise control of a non-constant total velocity in addition to control of the spatial position of the aircraft. From the pilot's standpoint, additional factors are therefore introduced which adversely affect his work-load and performance, such as:

- A requirement for active control of at least one additional controller (thrust magnitude).
- A requirement for additional displayed information concerning the increased dimensions of the task.
- Generally degraded aircraft flying qualities in the transition from aerodynamic to powered lift.
- Configuration change or thrust direction control (e.g. wing tilt, rotor tilt, jet thrust vectoring).

Studies of the VTOL instrument landing approach problem therefore involve ascertaining required levels of information presentation for the pilot and of stability and/or control augmentation for the aircraft. An excellent summary of this problem and recommendations for future research were given in 1972 in the AGARD Advisory Report on V/STOL display requirements for landing (Reference 1). The AGARD Working Group placed priorities on general research areas relevant to the problem that should be pursued as:

"a. System Theory and Design - Analysis and integration of sub-systems such as stability augmentation, pilot, displays, missions, etc.

b. Human Factors and Human Engineering Research - Determination of the pilot's response characteristics and their application to display design.

c. Operation - Accumulation of flight experience and the development of practicable flight procedures.

d. Technology - Development of the engineering ability to produce a display."

With respect to the first of these priorities, the Working Group noted that the interplay between display and control complexity was of major importance. The schematic representation of this interplay was given in Figure 1-1, and is repeated here as Figure 2-1. At the time of the AGARD report, these axes had not been quantified in any fashion, and so the first recommendation for future work given in Reference 1 was to perform studies relevant to the optimum mixture of display sophistication and automatic control complexity.

The most pertinent investigation for this experiment was therefore the examination of this control-display interplay by exploiting the variable stability capabilities of the X-22A aircraft to implement more than one type of control augmentation and by constructing a programmable display symbol generator to provide a variable display capability. On this basis, the primary purpose of the experiment was to provide meaningful data related to the interaction of aircraft control system and pilot display characteristics on pilot rating and performance during a steep decelerating descending transition from a representative forward velocity ($\sim$100 Kt) to the hover under instrument conditions. Accordingly, the experiment was designed to investigate combinations of several types of control system/stability augmentation characteristics with display presentations of varying sophistication, with the objective being the definition of satisfactory or acceptable combinations through the use of Cooper-Harper pilot ratings and measured performance and workload indices.

In order to ensure that the results from this experiment would both complement and supplement previous research in the area, as well as to provide a rational basis for the selection of variables, the most relevant studies which had been conducted were reviewed and drawn from when applicable. These studies are summarized in the next subsection.

2.3 RELATED PREVIOUS RESEARCH

The investigation used as one of the major starting points for this experiment was the initial VALT program work conducted at the NASA Langley Research Center using a CH-46 helicopter (References 5, 7, 8). The evaluation task

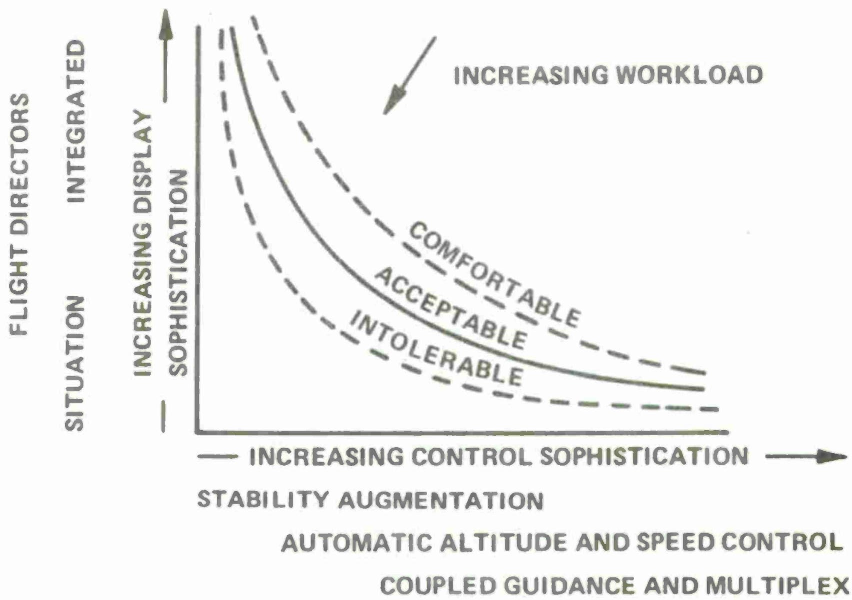


Figure 2-1 TRADE OFF BETWEEN DISPLAY AND CONTROL SOPHISTICATION (FROM REFERENCE 1)

consisted of an instrument approach along a steep glide path (6 degrees or 15 degrees) employing a deceleration from 45 knots to the hover, followed by a vertical let down. Since one of the primary objectives of this experiment was to extend the logic used for flight director design to completely automatic landings, no attempt was made to consider different types of display information or control augmentation. The control systems consisted of high-gain attitude-command systems in roll and pitch and a dual mode system in yaw which provided either automatic turn following or heading hold; the display presentation was centered on a three-axis flight director (pitch, roll, thrust) superimposed on the ADI and an electromechanical moving map which presented horizontal position and heading information. Major conclusions from the flight experiments were that, although good approach tracking performance was obtained, the attendant pilot workload was operationally unacceptable, and that a display which provided integrated status and command information was required.

A somewhat related experiment, but in this case using a fixed-base ground simulation of the CH-46 helicopter, was conducted prior to the VALT flight work by the NASA Electronics Research Center (Reference 9). The evaluation task consisted of instrument ILS approaches along a 6 degree glide path followed by a flare at approximately 1500 ft range, with an approach velocity of 42 Kt and a deceleration after the flare (not on the glide slope) to 10 Kt; evaluations under instrument conditions were conducted both for the complete task (to 100 ft range) and also for only the constant speed ILS tracking portion. The primary instrument was an electromechanical ADI with superimposed three-axis flight director elements -- no moving map or similar instrument was used.

The Reference 9 program did, however, perform an initial investigation of the control-display interaction problem by considering three types of manual control modes both with and without flight director information on the ADI. The control modes consisted of:

1. attitude command in pitch and roll, a dual mode yaw system, unaugmented vertical damping;
2. attitude command in pitch and roll, dual mode yaw system, vertical control augmentation giving rate-of-descent command and altitude hold;
3. longitudinal velocity commanded by pitch stick, course commanded by lateral stick, yaw and vertical augmentation as in the second system.

Major conclusions from the experiment were that, although all six possible combinations were operationally acceptable for the constant speed glide slope tracking, the simplest control mode was unacceptable both without and with the flight director information when the flare and deceleration were included. It is worth noting that the glide slope tracking portion of the evaluation task considered in this experiment corresponds to a STOL approach, and previous X-22A flight programs had demonstrated satisfactory pilot ratings for such approaches, using only raw ILS information, given good aircraft flying qualities (References 10, 11).

These two NASA programs provided the basis for an initial ground simulation experiment performed at the Calspan Corporation using the X-22A Ground Simulator Facility (Reference 12). The objectives of this program were to consider a more difficult task that would be representative of VTOL aircraft, as opposed to helicopters, and to investigate preliminary control system concepts designed for this application. Accordingly, the evaluation task consisted of tracking a 10 degree glide slope (localizer and glide slope acquisition were not included) on instruments from an initial condition duct (thrust vector) angle of 15 degrees, 100 Kt speed through a constant deceleration (either 0.05 g or 0.10 g) to a hover (duct angle of 90 degrees, zero speed) at 100 ft; included in the task was a "flare" to the hover altitude at 600 ft range while decelerating. The reasons for choosing this type of instrument approach task for VTOL aircraft are discussed in Section 3.0 of this report; its increased complexity over that used in the helicopter studies is a result of the requirements to follow a prescribed deceleration not "optimized" to the vehicle from a much larger initial velocity, and to change aircraft configuration during the approach.

For this investigation, the display presentation was not a variable; the displays were the same as in the VALT flight work, centering on a conventional ADI with superimposed three-axis flight director elements and on an electromechanical moving map as used in the CH-46 helicopter. In this case, as in the NASA ground simulation work, a small investigation of the control-display interaction problem was performed by considering variations in control augmentation; the systems consisted essentially of either attitude command augmentation with varying degrees of artificial height damping through glide-slope coupling, or of "direct velocity control" command augmentation in pitch and augmented height damping, whereby the pitch stick provided a longitudinal deceleration command by changing duct angle as well as attitude. The lateral control system was attitude command in all cases, and a dual mode directional system similar to the NASA designs was provided.

The conclusions from this experiment corroborated and expanded those from the helicopter programs. It was found, as in the NASA ground simulation experiment, that augmented height damping was required to perform the task with the attitude command control systems in conjunction with the three-axis flight director and moving map, and that providing even a relatively simple direct velocity control system substantially reduced pilot workload. A major conclusion, however, as in the NASA VALT flight experiments, was that increased integration of horizontal and vertical status and command information was required.

The X-22A ground simulator experiment, in conjunction with the two NASA experiments, provided the fundamental design framework for the flight experiment discussed in this report in terms of task and guidance requirements, but the control and display aspects were considerably expanded. This expansion was deemed necessary because of the following considerations noted from these three experiments:

1. The separated information presented on the two primary electromechanical displays used in the VALT work and the X-22A ground simulator program was considered marginally adequate at best and not operationally acceptable (References 5, 12). A need existed for increased integration of vertical and horizontal command and status information. In addition, the limited flexibility of the electromechanical instruments used did not permit a systematic investigation of some of the information requirements discussed by the AGARD Working Group (References 1, 13).

2. The requirement for VTOL aircraft to vary the thrust vector inclination by changing configuration in a prescribed fashion to achieve a commanded deceleration profile presents either an added dimension (fourth axis) to the problem of designing control directors or possibly a requirement for automating the changes. This control command was integrated with the longitudinal stick command in the initial X-22A ground simulator program, and it was noted that this procedure was satisfactory for the decelerating approach (Reference 12); in general, however, when control directors are used each control should have its own director element.

3. The relatively narrow range of angular augmentation concepts investigated in these programs needed to be expanded to ascertain more clearly the interplay with displayed information. In addition, both ground simulators indicated a need for increased height damping, whereas the flight experiment did not; this discrepancy, although typical when comparing fixed-base simulations with flight, warranted further attention in the context of improved display information to offset the lack of height damping.

With reference to the first consideration, two previous programs were most pertinent, the point of greatest significance being that each used the enhanced versatility offered by electronic display presentations (as opposed to electromechanical) to achieve the benefits of increased integration of status and command information. The first program was the moving-base ground simulation work in helicopter instrument hover display requirements performed by Dukes (at the U. S. Army Electronics Command) (References 14, 15), which was oriented primarily toward developing symbology to be superimposed over a video image to improve low visibility hover performance. The evaluation task consisted of precision hover at 75 ft; although a low speed approach was included to enhance the realism of the task, performance data were taken only during the hover. Only one control system, which had attitude command in pitch and roll plus heading hold and altitude hold for hover, was considered, but the control-display interplay problem was addressed by considering five levels of displayed information, which were essentially:

(1) video image only;
(2) video image with superimposed vertical position (altitude), pitch, roll and heading information, and raw airspeed and rate of climb data;
(3) the information of the second format plus horizontal translational rate information and altitude rate vector;
(4) the information of the third format plus ground-referenced horizontal position information;
(5) the fourth format without the video image.

Details of these formats as they affected the display design for the X-22A flight experiment will be discussed in Section VI of this report, but an important general result is that the explicit display of translational velocity information was imperative for good hovering performance. To provide velocity information in an integrated fashion, an electronic display is essential, and the results from this ground simulator program therefore demonstrated the need for such a display medium for the X-22A flight program.*

The second program which utilized the capabilities of an electronic display and was applicable to this X-22A experiment was the tripartite flight program conducted at the Naval Air Test Center using the Canadair CL-84 V/STOL aircraft equipped with a Smiths FLEXIHUD head-up display (References 16, 17). The program was conducted in two phases, the first of which evaluated a display format developed by the RAE and was considered the more relevant and useful. The task consisted of an instrument acquisition and tracking of a 4 degree glide slope at constant speed (90 Kt), a flare to level flight at 200 ft, 90 Kt, followed by a level deceleration still on instruments in level flight at 200 ft until approximately 1000 ft range when breakout occurred (~45 Kt speed). Control system variations were not considered: the basic CL-84 control system consisted of rate augmentation in roll and yaw and rate plus attitude augmentation in pitch, and could not be varied. Likewise, only one display format was investigated in this phase, although its characteristics had been evolved by ground simulation and were modified somewhat during the flights; the format combined integrated horizontal and vertical raw position information by showing glide slope brackets and a moving landing pad, and also included horizontal translational velocity information in a "guidance vector" command presentation. One of the major results from the program was again the extreme difficulty of tracking altitude, even with the deceleration occurring in level flight, and it was suggested that a power (collective) control director might be required. This display format provided design guidance for the velocity command format investigated in this X-22A program, as is discussed in Section VI of this report.

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* The authors are indebted to Messrs. T. Dukes and D. Carter of Princeton University for the loan of their ICL display symbol generator during the design of this flight experiment. This unit was used for the experiment design phase on the X-22A ground simulator, which is summarized in Appendix III of this report, and enabled us to consider an expanded configuration matrix.

With regard to the second consideration noted earlier (the requirement to change configuration), a flight investigation conducted by the NASA Ames Research Center using the XV-5B aircraft was pertinent (Reference 18). In this experiment, 10° ILS approaches were flown under visual conditions employing a deceleration from 70 knots to the hover. The XV-5B, like the X-22A, requires a configuration change to perform the desired deceleration: in the XV-5B, the fan exit louver angle is changed to alter the thrust vector inclination. Although the experiment was not specifically concerned with display/director studies, it was nonetheless clear that some "director" information was required to aid the pilot in changing configuration to meet the deceleration schedule. In the XV-5B, this information was presented as a command thrust vector angle as a function of altitude on the altimeter, which provided somewhat coarse director commands. Even so, one recommendation from the study was that the thrust vectoring be automated. The need to aid the pilot in performing configuration changes was also shown for STOL aircraft in a moving-base ground simulation conducted by Systems Technology, Inc. (Reference 19). The task consisted of level deceleration from 120 Kt to 60 Kt on instruments using a simulation of the Augmentor Wing Jet STOL Research Aircraft, which required both flap and engine nozzle changes with concomitant power variations. It was found that fully automating this procedure provided the largest improvement in pilot ratings, but that even "directing" the pilot to follow an ordered sequence of changes per a placard also provided some improvement. These two programs provided the impetus for conceiving and developing the Independent Thrust Vector Inclination Command (ITVIC) director logic (see Section IV of this report), and for investigating automatic duct rotation as one control system concept (see Section V).

In addition to the studies discussed above, flight testing of several existing VTOL concepts was performed by the NASA Langley Research Center in attempting to define VTOL control design requirements for the instrument approach task, one review of which is contained in Reference 20. Based on instrument flight evaluations of the XC-142A, DO-31, and SC-1 aircraft, in addition to the VALT CH-46 results, it was concluded that:

(1) Attitude command in pitch is required.

(2) Rate command attitude hold in roll is desirable.

(3) Turn coordination (zero sideslip) directional augmentation is required

It is emphasized that these conclusions were made independent of the displays used, and hence do not address the control-display interaction problem directly. The important point for this X-22A experiment is that these suggestions, and similar ones discussed in the full AGARD report on display requirements (Reference 13), are for the minimum augmentation complexity deemed necessary regardless of display sophistication. With reference to the third consideration noted earlier, however, many existing VTOL aircraft, such as the AV-8A/Harrier (e.g. Reference 21), have simpler systems consisting of angular rate augmentation only, and this fact influenced the experiment design to include these simpler augmentation types (Section V).

Another study relevant to the third consideration was a fixed-base simulation of the CH-3E helicopter conducted by the Air Force Flight Dynamics Laboratory (Reference 22). This program took a novel approach to the control-display interaction problem by providing a "blended" control system in pitch which sent all command information of frequencies greater than 0.5 rad/sec to the control servo and displayed to the pilot only that information of content less than 0.5 rad/sec; the lateral control was attitude command, and the directional axis was automatic turn following. The primary display was an electromechanical ADI with superimposed three-axis flight director commands, with the pitch command being the low-frequency information from the commands. Since the program was exploratory, the task consisted of only tracking a constant altitude and airspeed, and the major result was that the performance of this simple tracking task was improved by frequency-splitting the command information. Although interesting, this concept for control system design was not considered for investigation in the X-22A experiment because, as is discussed in Reference 13, its use in projected VTOL hardware systems would deprive the pilot of necessary information in the event of a failure.

The experimental programs which have been discussed in this subsection had the major influence on the design of this X-22A flight experiment. As was mentioned, a plethora of theoretical considerations relevant to specific aspects of the guidance relationships, control system characteristics, and display design philosophies can be found in the literature and will be discussed in the applicable sections of this report; these aspects were used in conjunction with the results of the experimental programs to define in broad terms the many factors possible for consideration as variables in this flight experiment. An outline of these factors is given in the next subsection.

2.4 POSSIBLE EXPERIMENTAL VARIABLES

Based on the background information reviewed in the previous subsection, the major factors which had to be considered in the design of this flight experiment may be summarized as:

1. Task Variables

   - initial velocity and altitude (representative of helicopters; representative of VTOL aircraft; civilian or military application)
   - localizer and glide slope interception (inclusion in task; procedure)
   - approach trajectory geometry (straight; curved; flare included)
   - range and/or altitude for breakout to visual conditions (all IFR; combination)
   - deceleration values and profiles (level or descending; constant, exponential, or "optimized")
   - wind and turbulence (crosswinds; headwinds; shears)

2. Guidance Information Variables

- available ground-based position information (none; azimuth and elevation; azimuth, elevation, and range; X,Y,Z coordinates)
- translational rates (ground derived; aircraft derived; none)
- command references (ground or air; earth axes or aircraft axes)
- command relationships (range rate or deceleration vs range; command limiting; hover-oriented or functions of configuration)

3. Control System Variables

- type of augmentation (angular rate; angular attitude; vertical rate; translational rates)
- degree of automation (none; automatic configuration change; partial or full coupling to guidance data)
- level of augmentation (time constants; frequency and damping; decoupling)
- control characteristics (gearings; force gradients; transport time lags)
- design philosophy (open-loop characteristics; optimal control; frequency separation)

4. Display Presentation Variables

- type and medium (separate or integrated; head up or head down; electromechanical or electronic; vertical, horizontal and/or profile)
- displayed information (positions; positions plus velocities; absolute or error information; control director information)
- symbology (analog or digital; choice of symbols; sensitivities)
- control director design philosophy (control "demand" or "command"; pilot-centered or closed-loop characteristics; command senses; frequency separation)
- additional information (configuration change)

The selection process by which the factors selected for variation were chosen is summarized in the following subsection.

2.5 SELECTION OF EXPERIMENTAL VARIABLES

Many of the factors listed in Section 2.4 are interrelated, and it was clearly beyond the scope of a 45 hour flight experiment to isolate their individual effects on pilot rating and performance. To achieve the objectives discussed in Section 2.2, it was necessary to concentrate on control system and display presentation variations, and therefore the guidance and task

factors were held essentially fixed. The NASA VALT Program (References 5, 7, 8) and the initial X-22A ground simulator experiment (Reference 12) were used as a guide for the selection of the guidance and task characteristics to be used; the control system concept used in the VALT work was used as a baseline around which several other types both less and more complex were designed, and the display variations were based on adding a head-down programmable electronic display capability. The resulting selections were investigated, modified, and verified on the X-22A ground simulator prior to flight implementation. It is emphasized that this procedure was part of the design process, and was not intended to be a ground simulator experiment; a summary of the conduct of it is given in Appendix III of this report.

Specifically, the evaluation task was a complete instrument landing approach similar to that used in Reference 12. It was not considered feasible in a limited flight program to investigate independently the effects of break-out to visual conditions or of different types of deceleration profiles; both of these factors may, however, have significant influence, and further research in these areas is desirable. The definition, details, and applicability of the selected task are discussed in Section III of this report.

The guidance relationships were again drawn from Reference 12, with some additions conceived and developed during the course of the present experiment. These relationships were based on the availability to the aircraft of X,Y,Z data obtained from a tracking radar; variations in the available ground-based information were not within the scope of this program. The guidance design is described in Section IV of this report.

For the control system variations, the diverse views on how much control system automation and augmentation is required -- and the dichotomy between what is desired and what is generally built into VTOL aircraft -- resulted in choosing the type of system and degree of automation to be the major variables. It was not possible to consider variations in the dynamic characteristics of each type; as a result, the design process consisted of picking these characteristics to be consistent with previous work and to meet the requirements of MIL-F-83300 where possible. Section V describes the type of control systems investigated.

The major display variable was the integrated electronic display format, with the intent being to present the pilot with generic levels of displayed information. The major influences on the format designs were the work of Dukes (Reference 14) and the CL-84 work (Reference 16), although considerable modifications were made during the ground simulation design phase. It was not considered useful to vary symbology or design philosophy, and only a brief investigation of the effects of separated information was performed as a check on the VALT results. A complete description of display design theory and applications to this experiment is given in Section VI.

As a summary of what was fixed and what was variable in this experiment, Table 2-1 repeats the factors outlined in Section 2.3 divided according to this selection.

Table 2-1

SUMMARY OF SELECTED EXPERIMENTAL VARIABLES

FACTOR	FIXED	VARIABLE
Task	Initial velocity and altitude. Localizer and glide slope. Approach geometry. Deceleration level and profile. No breakout to visual.	Winds, turbulence.
Guidance	Ground-based information. Translational rates. Switching between command references. Command relationships.	None.
Control Systems	Level of augmentation for each type. Control characteristics. Design philosophy.	Type of augmentation. Degree of automation.
Display Presentation	Head-down electronic. Integrated vertical-horizontal. Symbology. Director design philosophy.	Separated information. Display information. Configuration change.

Section III

SELECTION OF THE EVALUATION TASK

Because of the lack of standard flight procedures for VTOL instrument operations in the terminal area, special care was taken in the selection of the specific tasks to be accomplished for each evaluation. To ensure the credibility and validity of the experimental results, the approach conditions chosen for the evaluation task were required to be at once realistic and representative of the type of instrument landing approach which will conceivably be required of vectored-thrust V/STOL aircraft in both civil and military applications. Safety of flight requirements such as the presence of a safety pilot and the simulated instrument conditions provided necessary limitations to the realism of the task, while basic X-22A operating limits dictated some aspects of the selected approach trajectory. The remainder of this section describes the evaluation task and the rationale for its selection.

The evaluation task, as diagrammed in Figure 3-1, consisted of the following elements:

- level flight localizer acquisition (1700 ft AGL, 100 kt airspeed)
- constant speed glide slope acquisition (7.5 degrees) at approximately 12,000 ft range
- constant deceleration (.05g) on the glide slope, commencing at a range dependent on headwind (zero-wind range approximately 8000 ft)
- flare to level final approach commencing at approximately 1000 ft range, final altitude 100 ft, deceleration continuing to hover
- hover at 100 ft above simulated pad, vertical airwork as desired.

The steeply inclined decelerating approach to the hover is compatible with requirements dictated by CTOL traffic avoidance, obstacle clearance, fuel consumption, noise, and time considerations, and has been used almost exclusively in research conducted by both the NASA Ames and Langley Research Centers (References 5, 18). More complex approach trajectories involving curved flight paths and guidance in four dimensions (including time) require relatively sophisticated ground-based guidance systems such as MLS; although a SPN-42 tracking radar system was used to supply position data for this experiment, a less complex guidance system such as an ILS and precision DME could have served the same purpose had a breakout to visual conditions been included in the evaluation task.

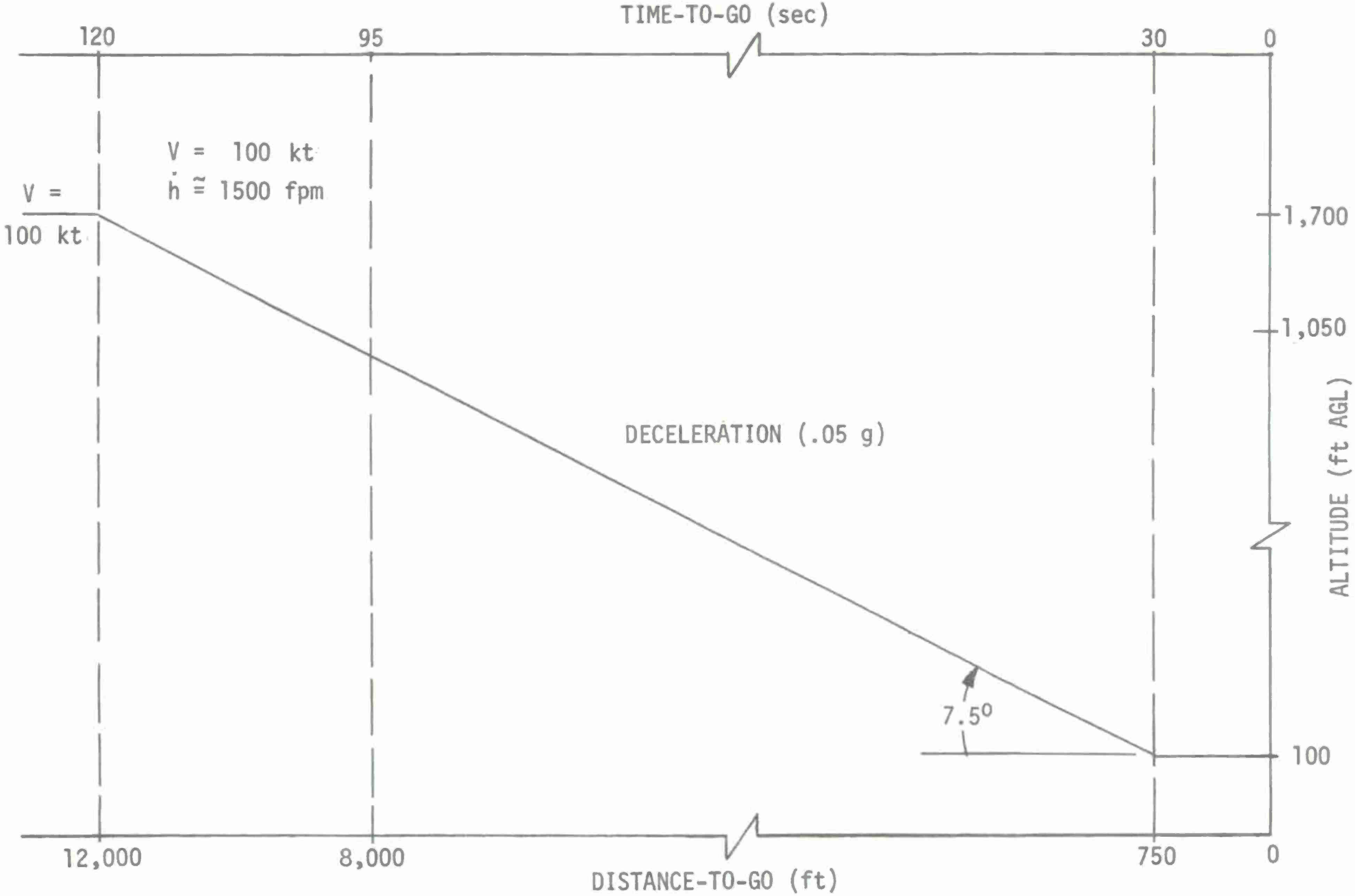


Figure 3-1 ZERO-WIND APPROACH TRAJECTORY

The initial phase of the evaluation task was the level flight localizer acquisition. An initial altitude of 1700 ft AGL was selected as an acceptable compromise between the requirement to minimize the aircraft's noise footprint prior to glide slope intercept and the need to have valid range information at least 15 seconds before intercept to generate the vertical guidance commands; this guidance system limitation is discussed in the following section. The initial airspeed of 100 kts was selected as an approach speed well within the aircraft's transition boundaries for both level and descending flight, and is representative of low-speed flight prior to conversion for most VTOL aircraft. A duct angle of 15 degrees allowed a trim pitch attitude of 5 degrees nose-up in level flight and zero degrees for descending flight; a zero degree duct angle would have required an uncomfortably large nose-up pitch attitude for level flight at any reasonable approach speed and hence was rejected.

Although the initial ground simulator experiment (Reference 12) used a 10 degree glide slope, a 7.5 degree descent angle was selected for the actual evaluation flights. Preliminary flights indicated that the 10 degree descent angle did not provide sufficient margin from duct stall boundaries during both glide slope intercept and the deceleration; furthermore the resulting rates of descent before deceleration ($\sim$2000 fpm) were judged to be excessive at relatively low altitudes (less than 1000 feet AGL). The 7.5 degree glide slope provided a reasonable duct stall margin, and the resultant initial zero-wind descent rate ($\sim$1500 fpm) was acceptable down to the altitudes for deceleration.

As illustrated in Figure 3-1, a minimum of 25 seconds was provided for stabilization on the glide slope before commencement of the deceleration. Any headwind component would increase this time interval, serving both to delay the initiation of the deceleration command to a smaller value of range (an effect discussed further in the following section) and to reduce the groundspeed resulting from the constant airspeed portion of the approach; for example, a 10 Kt headwind allowed an additional 10 seconds for glide slope stabilization.

The deceleration phase of the evaluation task consisted of a constant .05g deceleration commencing on the glide slope and continuing through the level approach to the hover. The constant deceleration profile was selected over the more simply implemented exponential profile based upon the helicopter results of NASA Langley (Reference 5) and the P.1127 results of the RAE (Reference 23); the exponential profile results in excessively large deceleration levels initially followed by low levels near the hover causing an inordinate amount of time spent in the powered-lift portion of the approach. It should be emphasized that the constant deceleration profile is not "optimized" to the capabilities of the X-22A. In fact, this profile represents a more demanding task for the pilot/aircraft/display system than one "optimized" to a particular aircraft (e.g. constant attitude for helicopters); operational use of VTOL aircraft may require that they all follow identical deceleration profiles, and constant deceleration is reasonable from an implementation point of view and provides a realistic operational task.

The results of the preliminary ground simulator experiment (Appendix III) showed both that a .05g deceleration provided a reasonable evaluation task and that an exponential decay of the command deceleration near the landing pad was required for a smooth precision hover. Both of these findings were implemented for the actual evaluation flights.

With approximately 1000 feet-to-go, a gradual reduction in descent angle occurred; at this point in the approach the commanded groundspeed was approximately 35 Kts and the resultant descent rate was 475 fpm. For most tilt-thrust vehicles, the descent rate vs. airspeed boundaries are most restrictive during the transition from aerodynamic lift to powered lift which occurs at airspeeds from 30 to 50 knots; in order to avoid these duct stall, fan stall, or buffet boundaries and still retain their steep descent capabilities, V/STOL aircraft will probably be required to reduce their flight path angle prior to this critical airspeed region. In addition, the level terminal portion of the deceleration allows a precision hover under guidance at constant altitude (which would not be possible were the descent continued to touchdown) and an increased safety margin in case of an engine failure near the touchdown point.

The flare maneuver was completed with 500 feet to go at 100 feet AGL. Although an instrument hover capability is not currently a U.S. Navy requirement (the present goal is 700 feet range, zero ceiling for all Navy VTOL aircraft - Reference 24), the evaluation task continued into the hover on instruments. As previously discussed, the length of the flight program did not allow an investigation of the effects on pilot rating of breakout conditions. Since the experiment described in this report represents a pioneering effort in establishing V/STOL control/display requirements for landing, it was decided to look at the entire landing approach problem and therefore to include the instrument hover as part of the task. The performance of a vertical landing on instruments was eschewed as a required part of the task due to flight safety considerations, but was allowable as an option to the pilot. Vertical airwork to 50 feet AGL or lower was, however, included in the task, and the pilot was asked to comment on whether or not he could land.

The following section describes the generation of the guidance commands required for the approach trajectory selected for the evaluation task.

Section IV

GUIDANCE DESIGN

4.1 SYNOPSIS OF SECTION

The purpose of this section is to describe the guidance relationships used in this flight program. In the context of this experiment, the term "guidance" is defined as the processing of raw X, Y, Z position data telemetered to the aircraft from a tracking radar to obtain information concerning positions and velocities and to derive the desired command relationships. It is important to recognize that the VTOL terminal area problem generally requires knowledge of, and commands for, both translational rates and positions, either for display to the pilot to aid him in the deceleration or for processing by an automatic control system to perform this operation for him. In this experiment, the derivation of the required status and command information was performed entirely onboard the aircraft using a multipurpose airborne analog computer (Appendix VIII and Reference 25), and was therefore essentially independent of the equipment used to provide the raw X, Y, Z data. As was discussed in Section 2, neither the raw information (e.g. altitude, azimuth, and elevation information instead of X, Y, Z) nor the derived command relationships were considered as variables to be altered for investigation; the guidance relationships were designed and verified in the ground simulation design phase (Appendix III) and held fixed for the flight experiment.

For the descending decelerating approach task with a VTOL aircraft which was discussed in Section III, the following types of commands are required:

- Longitudinal velocity as a function of range (deceleration profile)
- Lateral velocity as a function of lateral position
- Aircraft configuration change as a function of commanded velocity
- Vertical position as a function of range (glide slope)
- Vertical velocity as a function of range

Of particular interest among these relationships as implemented in this program are the commands for the horizontal-plane velocities, which switch from airspeed-course commands to ground-referenced velocity components parallel and perpendicular to the desired course, and the configuration change command, which is used both for a duct rotation director and for the control systems employing automatic thrust vector rotation; the philosophy of and need for these commands were conceived and developed during this flight program, and are considered important developments for VTOL guidance. The following subsections describe the estimation of spatial position and velocity status

information in two axis systems, then define and describe the horizontal-plane velocity command switching and the configuration change command, and finally summarize the vertical plane position and rate commands.

4.2 ESTIMATION OF SPATIAL POSITIONS AND RATES

The first processing of the data is the estimation of smoothed translational positions and rates relative to a hover point and selectable approach course direction by complementary filtering of the radar position data and aircraft linear accelerometer outputs. This processing is required because the radar X, Y, Z data are too noisy for direct differentiation or for display to the pilot. The procedure is similar to that discussed in Reference 26: body-axis accelerometer information is transformed into an earth-referenced axis system and blended with the radar data in a second order filter. For this application, the Euler-angle transformation equations were simplified for implementation on the analog computer by the use of small angle assumptions, and are summarized in Equations 4-1:

$$\begin{bmatrix} \ddot{X}_e \\ \ddot{Y}_e \\ \ddot{Z}_e \end{bmatrix} = \begin{bmatrix} -\cos(\psi_N - \psi_A) & \sin(\psi_N - \psi_A) & 0 \\ \sin(\psi_N - \psi_A) & \cos(\psi_N - \psi_A) & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} a_x - g\theta \\ a_y + g\phi \\ a_z + g \end{bmatrix} \qquad (4\text{-}1)$$

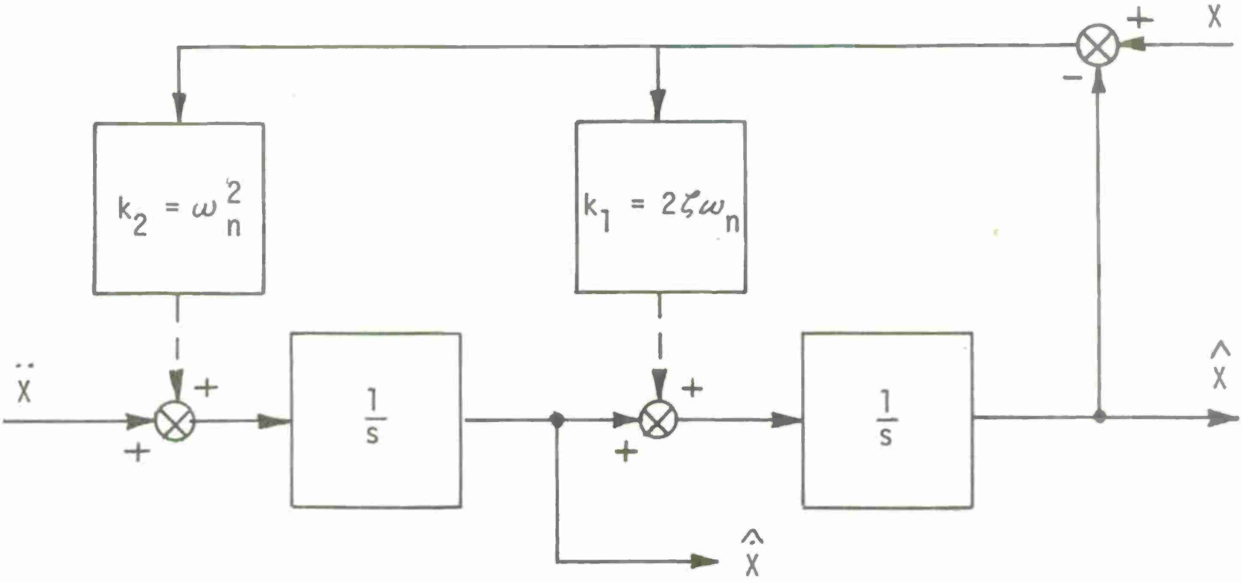
Note that the heading reference ψ_A is a selectable approach course heading; as will be discussed in Section VIII, five possible approach headings covering a 90 degree arc were available for use.

A schematic diagram of the complementary filters and resulting input-output relationships is given in Figure 4-1; the implementation on the onboard analog computer is shown in Appendix VIII. The selection of the gains which determine the natural frequency and damping ratio of the filters was based on modifying the minimum variance values to provide more rapid settling time and less sensitivity to accelerometer biases. The minimum variance values are found by applying Kalman filter theory to this second order example, which yields (where $\sigma_{\ddot{x}}$ and σ_x are accelerometer and radar noise standard deviations, respectively):

$$K_1 = \sqrt{2\sigma_{\ddot{x}}/\sigma_x} \qquad (= 2\zeta\omega_n)$$

$$K_2 = \sigma_{\ddot{x}}/\sigma_x \qquad (= \omega_n^2) \qquad (4\text{-}2)$$

The damping ratio is seen to be 0.707 always, while the natural frequency depends on the ratio of the noise statistics; for the X-22A application, these statistics result in a natural frequency of approximately 0.2 rad/sec. This value, however, leads to a settling time of approximately 30 seconds after



INPUT	OUTPUT	
	$\hat{\dot{X}}$	$\hat{X}$
$\ddot{X}$	$\dfrac{s + k_1}{s^2 + k_1 s + k_2}$	$\dfrac{1}{s^2 + k_1 s + k_2}$
X	$\dfrac{k_2 s}{s^2 + k_1 s + k_2}$	$\dfrac{s k_1 + k_2}{s^2 + k_1 s + k_2}$

$\ddot{X}$ is earth-referenced acceleration measurement

X is radar position data

$\hat{X}$, $\hat{\dot{X}}$ are earth referenced position and rate estimates, respectively

Figure 4-1 COMPLEMENTARY FILTER SCHEMATIC AND TRANSFER FUNCTIONS

the onset of radar information, which was considered too long given the maximum range available as will be discussed below. Hence, a frequency of 0.35 rad/sec was chosen to provide a settling time of approximately 15 seconds, and so the values of these gains as implemented were:

$$K_1 = 0.495$$
$$K_2 = 0.123 \qquad (4-3)$$

The estimation of positions and velocities involved the only aspects of the guidance relationships developed in this program that were a function of the ground equipment used. Specifically, a limited digital word length in the telemetry uplink (9 bits on X, Y; 7 bits on Z) introduced a necessity to provide scale changes for the data on all three channels and therefore to implement automatic relay switching in the complementary filters. The scale values were chosen to provide sufficient data resolution in the hover while ensuring adequate coverage during localizer and glide slope acquisition, and are summarized in Table 4-1 below.

Table 4-1

DIGITAL RADAR DATA SCALING

	X_e	Y_e	Z_e
Word Length	9	9	7
Max. Scale Range	512	512	128
Outer Scale:			
Feet/bit	40	40	20
Max. range (ft)	17,480	10,240	2560
Min. range (ft)	- 3,000	-10,240	0
Inner Scale:			
Feet/bit	2	2	2
Max. range (ft)	874	512	256
Min. range (ft)	-150	-512	0

In addition to these two scales, which were automatically switched at a range of approximately 640 feet, an additional manual scale change was available for hover ("Hover Mode"), which increased the Z resolution to 1 ft/bit. It should be noted particularly that the maximum range for valid X data is only 17,480 feet, which means that the complementary filter does not initiate estimating smooth position and rate data in this axis until that point; since glide slope acquisition occurs at approximately 13,000 ft range (Section III), approximately 20 seconds are available for X-filter settling prior to this point, which is the main reason the complementary filter frequency was increased from the minimum-variance value. The full scale ranges for Y and Z were sufficiently

large that this problem did not occur in these axes: valid Y and Z position and rate information was available immediately after radar lock-on.

The smoothed translational positions and rates that are the outputs of the complementary filters are in an earth-referenced axis system which has its origin at the landing point and its X -axis along the selected approach course("approach-course-up"). The relationship between this axis system, the aircraft body axes, and a "heading-up" axis system (origin at aircrft center of gravity, Z -axis vertical, X-axis rotated through $\psi_N - \psi_A$) is shown in Figure 4-2; to provide the position and rate information in either the approach-course-up or heading-up systems, all the complementary filter outputs are transformed through the following equations:

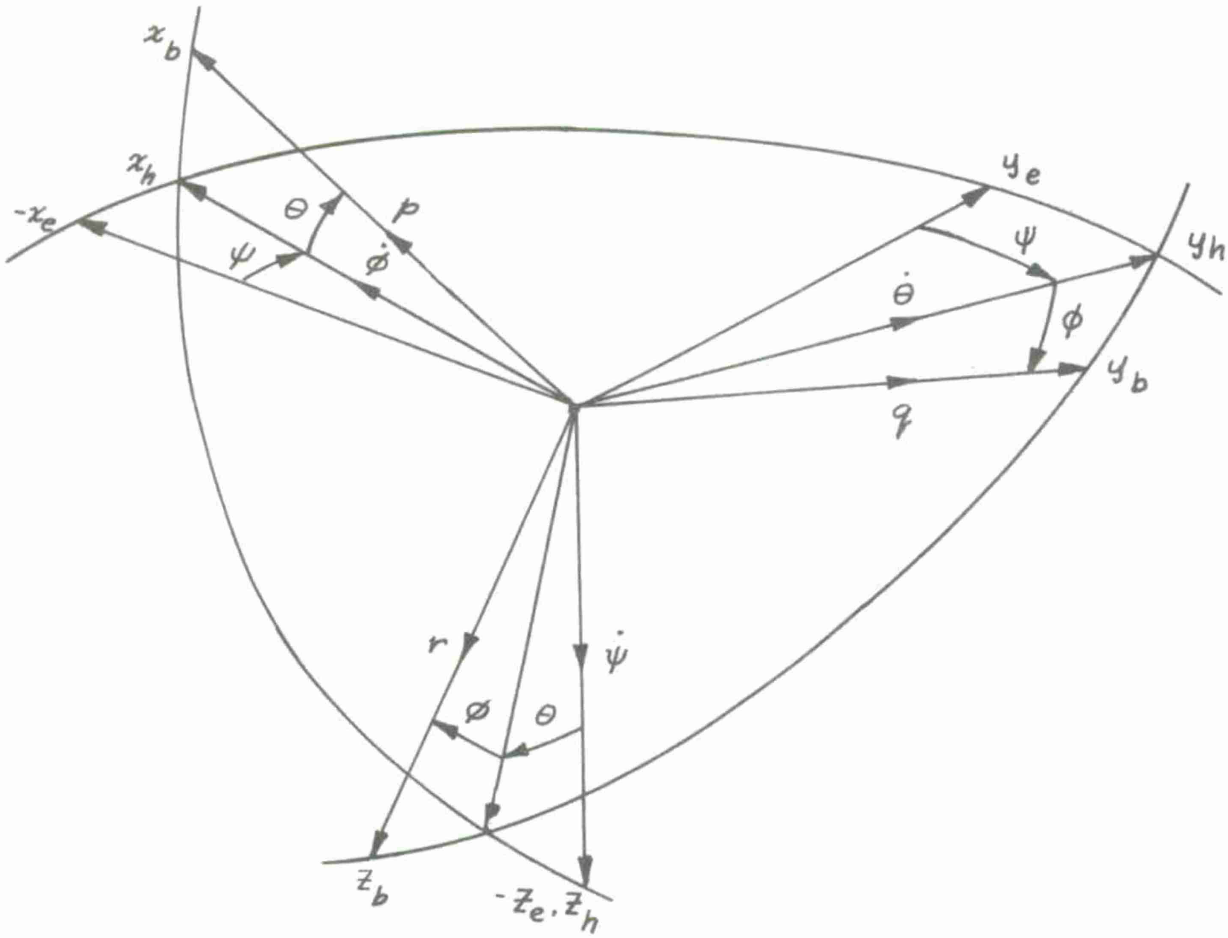
$$\begin{bmatrix} \hat{X}_h \\ \hat{Y}_h \\ \hat{Z}_h \end{bmatrix} = \begin{bmatrix} -\cos(\psi_N - \psi_A) & \sin(\psi_N - \psi_A) & 0 \\ \sin(\psi_N - \psi_A) & \cos(\psi_N - \psi_A) & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} \hat{X}_e \\ \hat{Y}_e \\ \hat{Z}_e \end{bmatrix}$$

With the position and velocity status information available, the generation of the command relationships may be performed. These commands are discussed in the following subsections.

4.3 HORIZONTAL-PLANE VELOCITY COMMANDS

4.3.1 General Discussion

A fundamental problem which must be addressed for VTOL decelerating approaches is the fact that the magnitude of the along-track wind velocity component can be a significant fraction of the commanded aircraft velocity, and in fact becomes comparable as the hover point is approached. If the commanded aircraft velocity is ground-referenced for the entire approach, which is the procedure that has been used in all previous experimental work (e.g. References 5, 9, 12, 16), then acquisition airspeed will vary from approach to approach, which complicates the pilot's task; more importantly, VTOL aircraft generally have relatively narrow corridors of acceptable airspeed/configuration (thrust tilt)/rate of descent combinations, and forcing differing airspeeds may violate these boundaries. One solution to the problem, proposed in Reference 27, is to refer the approach path and deceleration profile to the air mass by using either ground or aircraft measured wind velocity information to compute the transformation from ground-referenced to air-referenced coordinates. This technique ensures that both the path and the deceleration are always the same with respect to the air, thereby maintaining the aircraft within its allowable transition corridor. As a result, however, the ground track (approach angle, flare point) varies with different winds; in addition, as is emphasized by the AGARD Working Group (Reference 13), in or near the hover it is velocity with respect to the ground, both longitudinally and laterally, which must be controlled, and the commands should therefore be ground-referenced at this point.



- $\psi \triangleq \psi_N - \psi_A$

  ψ_N is aircraft heading *w.r.t* north

  ψ_A is approach centerline heading *w.r.t* north

- Subscripts

  "e" is approach-course-up ("earth") axes, nonrotating, origin at hover spot

  "h" is heading-up axes, rotation about Z-axis only, origin at aircraft center of gravity

  "b" is aircraft body axes, rotating, origin at aircraft center of gravity

Figure 4-2 COORDINATE SYSTEM DEFINITION

The desiderata for the horizontal-plane velocity commands may therefore be summarized as:

- Airspeed command during localizer and glide slope acquisition
- Aircraft course or heading during acquisition that accounts for the along-track and cross-track wind components
- Maintenance of an airspeed-configuration relationship that is within the aircraft's transition corridor
- Smooth, undetectable change to command of ground velocities
- Command of longitudinal and lateral ground velocity components during hover

To achieve these characteristics, the implementation of the velocity commands in this experiment consisted of considering the approach in two parts, and automatically switching the commands between the two parts based on the magnitude of the along-track wind component. The first part was the constant airspeed localizer and glide slope interception, during which longitudinal airspeed and aircraft heading were commanded; the second part consisted of the deceleration and hover, during which ground speed components parallel and perpendicular to the desired course were commanded.

The details of these commands and of the switching logic are given below. It will be noted that, as implemented in this experiment, the logic is constrained to cases in which only headwind and/or crosswind components are present. Although the extension to consider tailwinds is straightforward, it was assumed that the inherent flexibility of VTOL operations would generally result in approach courses at least partially into the wind, which is considered preferable particularly near the hover.

4.3.2 Acquisition Commands -- "Before Switching"

The airspeed and course commands are predicated upon the fact the LORAS airspeed measuring system of the X-22A (Appendix VIII) gives longitudinal and lateral components of airspeed relative to the aircraft heading axis, which, in conjunction with the ground-referenced rates from the complementary filters, allows determination of the wind speed and direction. It would, however, be possible to achieve similar results with other air data systems if necessary. Using the LORAS u, v measurements, the wind components in both the heading-up and approach-course-up earth-referenced axis systems are (assuming zero pitch and roll angles):

$$V_{w_{X_h}} = \hat{\dot{X}}_h - u$$

$$V_{w_{Y_h}} = \hat{\dot{Y}}_h - v \qquad \text{(4-4a)}$$

$$V_{w_{X_e}} = \hat{\dot{X}}_e + u \cos\psi - v \sin\psi$$

$$V_{w_{Y_e}} = \hat{\dot{Y}}_e - u \sin\psi - v \cos\psi \qquad \text{(4-4b)}$$

where: $(\ \ )_h$ is heading-up reference

$(\ \ )_e$ is course-up reference

$(\ \hat{}\ )$ is complementary filter output

$\psi \triangleq \psi_N - \psi_A$

These wind component estimates are now used in the derivation of the commands. The command situation is shown schematically in Figure 4-3: it is desired that the magnitude of the longitudinal airspeed be constant (u_c = 100 Kt), and that the aircraft course be steered to the approach centerline (Y_e = 0). The object is to relate these characteristics to velocity command components which can be displayed to the pilot directly or integrated into control director relationships. Since the "after switching" (AS) velocity commands will be ground-speed components, the "before switching" (BS) commands must be derived for presentation as ground speed components to avoid any transients in displayed information when switching takes place.

Starting with the commanded components in the heading-up system, we have from Figure 4-3:

$$\dot{X}_{h_c}\Big|_{BS} = V_{e_c} \cos(\Gamma_c - \psi)$$

$$\dot{Y}_{h_c}\Big|_{BS} = V_{e_c} \sin(\Gamma_c - \psi) \qquad \text{(4-5)}$$

where Γ_c is commanded course

In order to provide a smooth acquisition of the approach course centerline (Y_e = 0), the course command used in this program was:

$$\Gamma_c = K_\Gamma \hat{Y}_e , \quad K_\Gamma = -.02 \text{ degrees/foot} \qquad \text{(4-6)}$$

Γ_c limited at 30 degrees

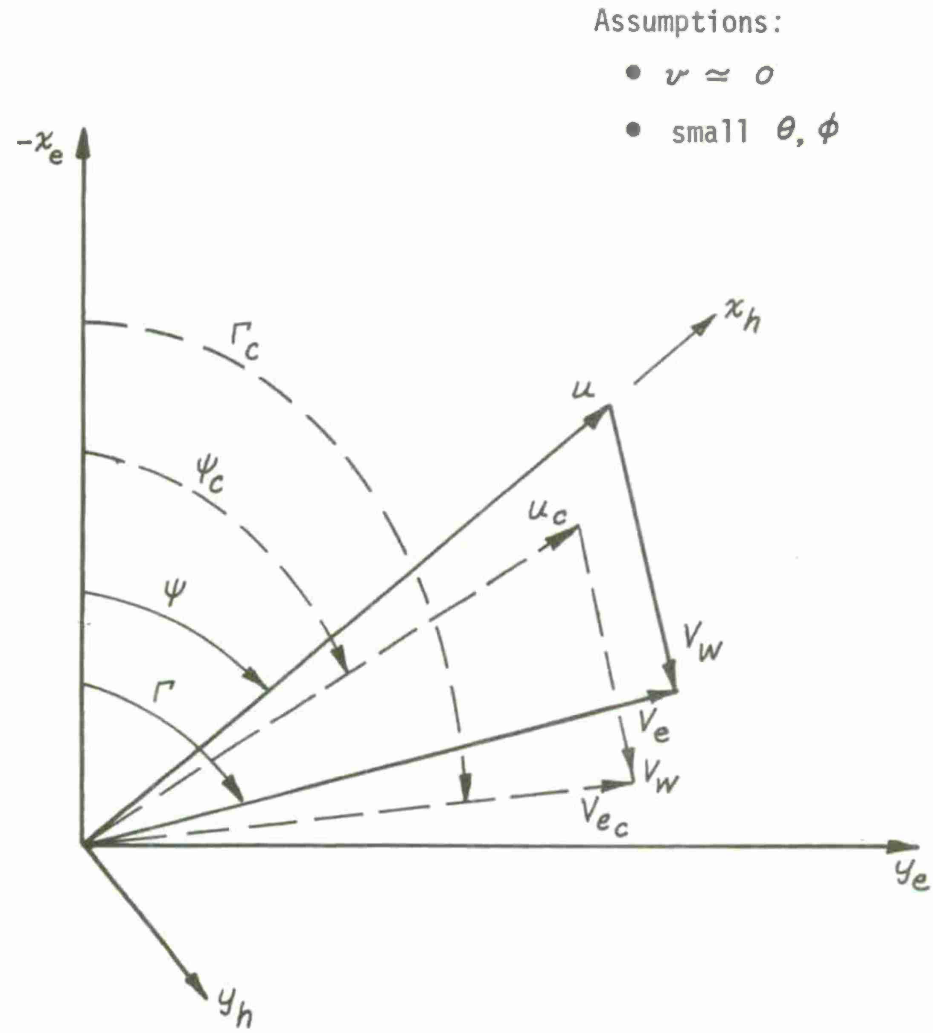


Figure 4-3 COMMAND VELOCITIES FOR AIRSPEED/COURSE TRACKING

This form for the command provides an exponential capture of the centerline with a time constant of approximately 17 seconds, and is consistent with the lateral command philosophies used in previous programs (References 9, 12).

The command relationships given in Equation 4-5 may also be written in terms of the "steering command" ψ_c as:

$$\dot{X}_{h_c}\Big|_{BS} = u_c \cos(\psi_c - \psi) + V_{w_{X_h}}$$
(4-7)
$$\dot{Y}_{h_c}\Big|_{BS} = u_c \sin(\psi_c - \psi) + V_{w_{Y_h}}$$

where ψ_c is the commanded aircraft heading dependent on wind.

Assuming good tracking of heading (small $\psi_c - \psi$), and substituting from Equation 4-4a, the first of the relationships in Equation 4-7 may be written immediately as:

$$\dot{X}_{h_c}\Big|_{BS} = u_c + \hat{\dot{X}}_h - u \triangleq \hat{\dot{X}}_h - \Delta u \qquad (4\text{-}8)$$

The second command in Equation 4-7 must be related to the commanded course; from Figure 4-3, assuming $\Gamma_c - \psi_c$ "small":

$$\psi_c = \Gamma_c + \frac{V_{w_{X_e}} \sin \Gamma_c - V_{w_{Y_e}} \cos \Gamma_c}{u_c} \qquad (4\text{-}9)$$

$$\cong \left(1 + \frac{V_{w_{X_e}}}{u_c}\right)\Gamma_c - \frac{V_{w_{Y_e}}}{u_c} \qquad (4\text{-}10)$$

if Γ_c is assumed small (recall $\Gamma_c \leq 30$ degrees)

Equation 4-10 shows that two corrections must be applied to the course command to obtain a heading steering command which accounts for winds. The along-track wind component ($V_{w_{X_e}}$) modifies the magnitude of the course command, while the cross-track component ($V_{w_{Y_e}}$) introduces an additional steering command. The magnitude correction is the less important of the two: since the commanded course is a linear function of lateral offset Y_e, the correction is equivalent

to choosing a different proportionality constant. In addition, $V_{w_{x_e}}$ requires valid $\hat{X}_e$ information, and is therefore unobtainable beyond 17,480 feet range. This correction is therefore neglected in the implementation, but the additional steering correction due to the cross-track wind is retained. Substituting into Equation 4-7, using $\sin\psi \cong \psi$ because of equipment limitations, and simplifying gives:

$$\dot{Y}_{h_c}\Big|_{BS} = u_c K_r \hat{Y}_e - \hat{\dot{Y}}_e + \Delta u \sin\psi + \hat{\dot{Y}}_h \qquad (4\text{-}11)$$

Equations 4-8 and 4-11 are the desired ground component velocity commands to provide a constant airspeed and aircraft steering to the approach centerline. They are implemented on the airborne analog computer (Appendix VIII) either for display directly to the pilot or for use in the generation of control director commands. Since display presentations in the approach-course-up reference system were also desired (see Section VI), the commands in these axes are obtained by the coordinate transformation and implemented as:

$$\begin{aligned} \dot{X}_{e_c}\Big|_{BS} &= -\dot{X}_{h_c}\Big|_{BS} \cos\psi + \dot{Y}_{h_c}\Big|_{BS} \sin\psi \\ \dot{Y}_{e_c}\Big|_{BS} &= \dot{X}_{h_c}\Big|_{BS} \sin\psi + \dot{Y}_{h_c}\Big|_{BS} \cos\psi \end{aligned} \qquad (4\text{-}12)$$

It is worth noting the implications on these commands of the limited range for which valid radar X data is available. Since $\dot{X}_{h_c}\big|_{BS}$ and $\dot{Y}_{h_c}\big|_{BS}$ are dependent on $\hat{\dot{X}}_h$ and $\hat{\dot{Y}}_h$, respectively, which in turn depend on having valid $\hat{X}_e$ and $\hat{Y}_e$ information because of the coordinate transformation, their values are not correctly computed until the 17,480 feet range has been passed inbound on the approach. For the display formats which present velocity command (and velocity) information (as will be described in Section VI), therefore, this limitation implies a limited usefulness of the horizontal velocity data presentation prior to 17,480 feet, although vertical position and velocity information is, of course, valid. For the formats which include control directors, however, the philosophy of commanding airspeed and heading in the first part of the approach results in valid director information even before 17,480 feet. The reason is that, as will be discussed in Section VI, the control directors use the velocity errors $\dot{X}_{h_c} - \hat{\dot{X}}_h$ and $\dot{Y}_{h_c} - \hat{\dot{Y}}_h$ in the command logic; as can be seen from Equations 4-8 and 4-11, these velocity errors are independent of $\hat{X}_e$, and, since Y_e displacement never exceeded the maximum scale at radar lock-on, the error information was valid immediately.

To summarize, airspeed magnitude and aircraft heading are commanded during the first part of the approach. Estimates of the wind velocity derived from onboard air sensors and the telemetered radar information are used to compute the commands necessary to account for along-track and cross-track wind components. The commands are calculated as ground-referenced velocity components to eliminate any displayed information transients when the switch to ground speed commands is made for deceleration and hover.

4.3.3 Switching Logic and Deceleration Commands -- "After Switching"

For the "after switching" part of the approach, the ground velocity parallel to the desired course is commanded based on a constant deceleration (0.05g) with a linear decrease to zero during the final 100 feet, and the component perpendicular to the course as a linear function of lateral position. The lateral command is scaled to be consistent with the course command used prior to the switching, and is:

$$\dot{Y}_{e_c}\Big|_{AS} = K_1 \hat{Y}_e \tag{4-13}$$

$K_1 = -.057$ ft/sec/ft

$\dot{Y}_{e_c}$ limited to 85 ft/sec

The parallel component command is implemented as a zero-wind velocity profile versus range on a function generator in the aircraft, and is shown in Figure 4-4. The function generator approximates the following relationships:

$$\begin{aligned}
\dot{X}_{e_c}\Big|_{AS} &= 170 \text{ ft/sec}, & \hat{X}_e &\gtrsim 8000 \text{ ft} \\
\dot{X}_{e_c}\Big|_{AS} &= K_2\sqrt{\hat{X}_e}, & 8000 &> \hat{X}_e > 100 \text{ ft} \\
&= K_3 \hat{X}_e, & -100 &< \hat{X}_e < 100 \text{ ft} \\
&= -K_2\sqrt{|\hat{X}_e|}, & \hat{X}_e &< -100 \text{ ft}
\end{aligned} \tag{4-14}$$

$K_2 = -1.9$

$K_3 = -.19$

It is emphasized that this command is for the ground speed velocity component parallel to the desired approach course ($\dot{X}_e$), and in zero-wind conditions corresponds to the logic used in previous programs for the entire approach trajectory (References 5, 12), with a deceleration initiation at approximately 8000 feet range.

This implementation serves the dual purpose of providing the deceleration commands "after switching" and also of defining the point at which the switching of command logic from airspeed/heading to ground speed component tracking takes place. To provide the information which triggers the logic switching, the aircraft's measured ground speed in the heading-up axis system ($\hat{\dot{X}}_h$) is continuously subtracted from the zero-wind command:

$$\dot{X}_{h_c}\Big|_{\substack{ZERO\\WIND}} = \dot{X}_{h_c}\Big|_{AS} = -\dot{X}_{e_c}\Big|_{AS}\cos\psi + \dot{Y}_{e_c}\Big|_{AS}\sin\psi \tag{4-15}$$

$$\dot{X}_{h_c}\Big|_{AS} - \hat{\dot{X}}_h \triangleq \epsilon_{\dot{X}_h} \tag{4-16}$$

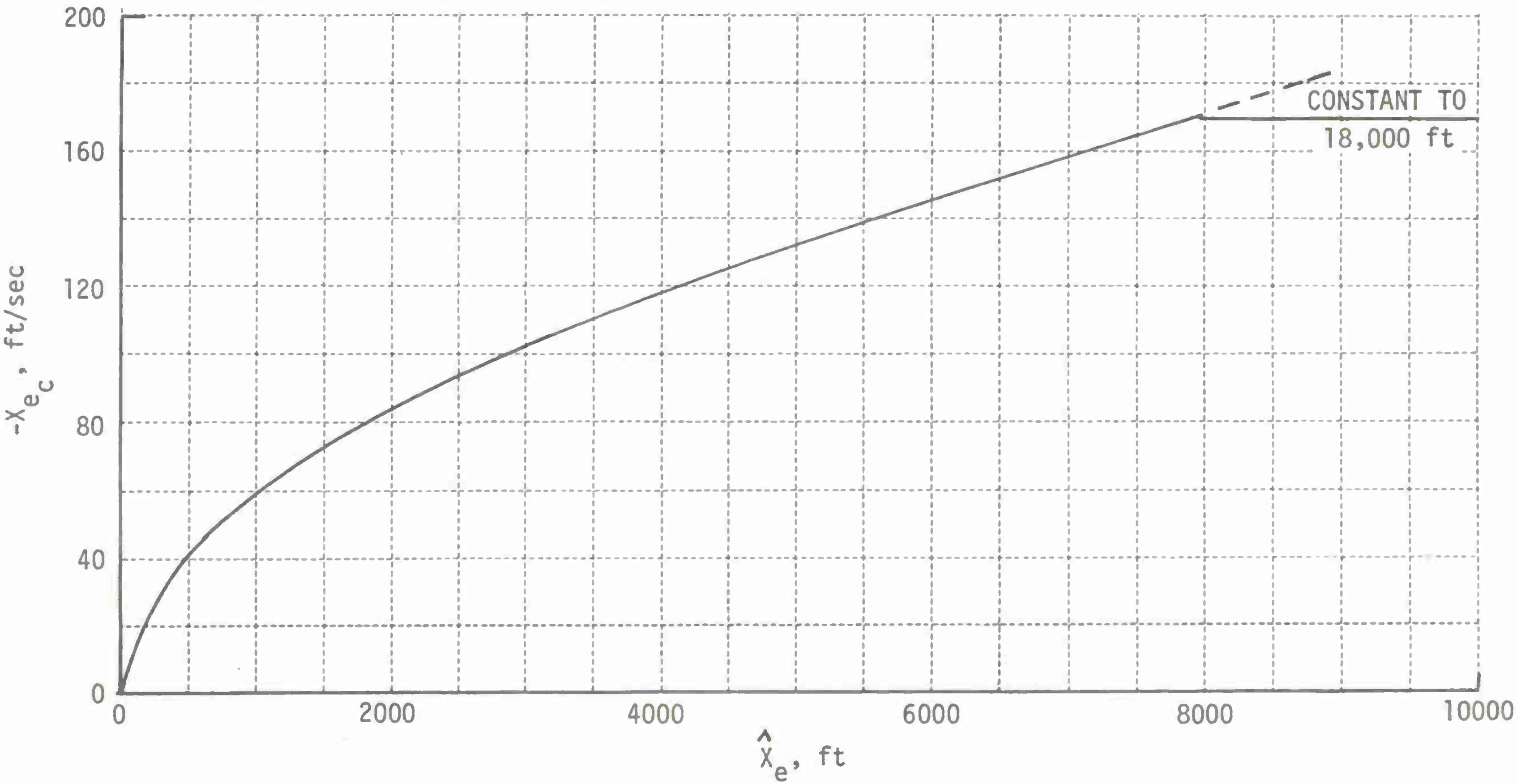


Figure 4-4 DECELERATION PROFILE

If there is a headwind component along the desired course, this difference will be positive until the commanded ground speed starts to decrease after the zero-wind deceleration initiation point. An example situation, assuming the aircraft on course with a 20 Kt headwind, is shown in Figure 4-5. With the pilot tracking the "before switching" 100 Kt airspeed command, it can be seen that $\dot{X}_{h_c}|_{AS}-\hat{\dot{X}}_h$ is positive until approximately 5050 feet range (X_e), at which point the commanded ground speed has reduced to 80 Kt so that $\dot{X}_{h_c}|_{AS} = \hat{\dot{X}}_h$. Note that this point is almost 3000 feet closer to the hover spot than the zero-wind deceleration initiation point. From this point on, the aircraft must decelerate following the ground speed commands to arrive at the hover point with zero speed relative to the ground (although airspeed will be 20 Kt). By following the ground speed commands starting closer in, the same deceleration (.05g) is required regardless of headwind.

The logic switching point was therefore determined by:

$$\dot{X}_{h_c}\Big|_{AS} - \hat{\dot{X}}_h = \epsilon_{\dot{X}_h} \Longrightarrow 0 \tag{4-17}$$

The implementation consisted of monitoring this signal continuously after radar lock-on; when it first became zero, relays were tripped which switched the signals available for display or control system processing from the "before switching" values (Equations 4-8, 4-11) to the "after switching" values (Equations 4-13, 4-13). Hysteresis was deliberately introduced in the relays to ensure that "flip-flopping" of the command switching did not occur.

It is useful to conclude the discussion of the command switching process by considering possible transients in the command or error information which may occur at the switching point. The simplest way to see any such effects is to consider the commanded velocities in the heading up axes as referred to the ground minus the actual velocities; hence:

$$\dot{X}_{h_c}\Big|_{BS} - \hat{\dot{X}}_h = -\Delta u \tag{4-18a}$$

$$\dot{Y}_{h_c}\Big|_{BS} - \hat{\dot{Y}}_h = u_c K_r \hat{Y}_e - \hat{\dot{Y}}_e + \Delta u \sin\psi \tag{4-18b}$$

$$\dot{X}_{h_c}\Big|_{AS} - \hat{\dot{X}}_h = -\epsilon_{\dot{X}_e}\cos\psi + \epsilon_{\dot{Y}_e}\sin\psi = \epsilon_{\dot{X}_h} \tag{4-18c}$$

$$\dot{Y}_{h_c}\Big|_{AS} - \hat{\dot{Y}}_h = \epsilon_{\dot{Y}_e}\cos\psi + \epsilon_{\dot{X}_e}\sin\psi \tag{4-18d}$$

$$\epsilon_{\dot{X}_e} \triangleq \dot{X}_{e_c}\Big|_{AS} - \dot{X}_e$$

$$\epsilon_{\dot{Y}_e} \triangleq \dot{Y}_{e_c}\Big|_{AS} - \dot{Y}_e$$

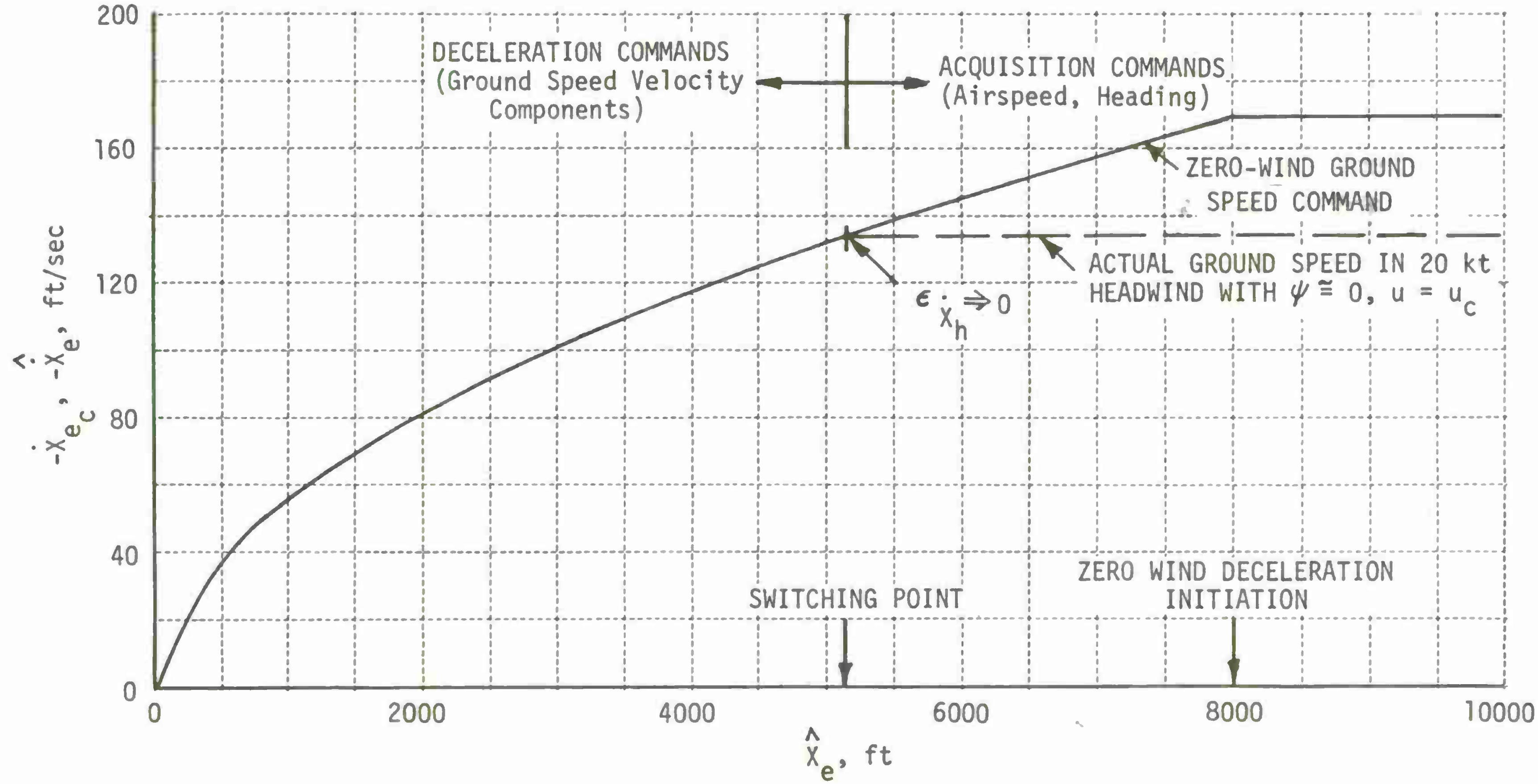


Figure 4-5 EFFECT OF HEADWIND ON DECELERATION PROFILE

At the switching point, $\epsilon_{\dot{X}_h} = 0$. Comparing Equation 4-18a with 4-18c, therefore, it can be seen that the transient will depend on Δu ; since the pilot is attempting to maintain $\Delta u = 0$ during airspeed tracking, this transient is generally small. Referring to Equation 4-13 and noting that $K_1 = u_c K_r$, Equation 4-18b can be written as:

$$\dot{Y}_{h_c}\Big|_{BS} - \hat{\dot{Y}}_h = \epsilon_{\dot{Y}_e} + \Delta u \sin\psi \tag{4-19}$$

Using the fact that $\epsilon_{\dot{X}_h} = 0$ at switching in Equation 4-18c and substituting into 4-18d, that equation becomes:

$$\dot{Y}_{h_c}\Big|_{AS} - \hat{\dot{Y}}_h = \frac{\epsilon_{\dot{Y}_e}}{\cos\psi} \tag{4-20}$$

Comparing Equations 4-19 and 4-20, the transient is again seen to be negligible for good airspeed tracking and realistic aircraft headings with respect to the approach course.

4.3.4 Summary of Horizontal-Plane Velocity Commands

The "before switching" and "after switching" velocity commands referred to the ground in both the approach-course-up and heading-up reference systems are summarized in Table 4-2 below.

Table 4-2

HORIZONTAL VELOCITY COMMANDS

	Acquisition Commands "Before Switching"	Deceleration Commands "After Switching"
Approach-course-up	$\dot{X}_{e_c} = -\dot{X}_{h_c}\big\|_{BS}\cos\psi + \dot{Y}_{h_c}\big\|_{BS}\sin\psi$ $\dot{Y}_{e_c} = \dot{X}_{h_c}\big\|_{BS}\sin\psi + \dot{Y}_{h_c}\big\|_{BS}\cos\psi$	$\dot{X}_{e_c} \cong K_2\sqrt{\hat{X}_e}$ $\dot{Y}_{e_c} = K_1\,\hat{Y}_e$
Heading-up	$\dot{X}_{h_c} = \hat{\dot{X}}_h - \Delta u$ $\dot{Y}_{h_c} = u_c K_r\,\hat{Y}_e - \hat{\dot{Y}}_e$ $+ \Delta u \sin\psi + \hat{\dot{Y}}_h$	$\dot{X}_{h_c} = -\dot{X}_{e_c}\big\|_{AS}\cos\psi + \dot{Y}_{e_c}\big\|_{AS}\sin\psi$ $\dot{Y}_{h_c} = \dot{X}_{e_c}\big\|_{AS}\sin\psi + \dot{Y}_{e_c}\big\|_{AS}\cos\psi$

The point at which the switching between these two sets of commands takes place is defined by

$$\dot{X}_{h_c}\Big|_{AS} - \hat{\dot{X}}_h \Rightarrow 0$$

4.4 CONFIGURATION CHANGE COMMAND (ITVIC)

4.4.1 General Discussion

VTOL configurations different than the helicopter require substantial configuration changes to convert from forward flight to powered lift in the hover. For jet-lift aircraft (e.g. Harrier AV-8A, Dornier DO-31), the conversion process can be quite flexible, since allowable combinations of thrust inclination and airspeed are relatively unconstrained; for aircraft types which rotate relatively large aerodynamic surfaces, such as tilt-wing or tilt-duct, however, a fairly narrow corridor of combinations exists to avoid flow separation. For these latter types, therefore, automatic configuration changes may be required; at the very least, the pilot should be provided with director information to help him perform the conversion safely. In a more general sense, the conversion process for any VTOL aircraft under advanced terminal area operational concepts such as 4-D guidance (Reference 28) may require precisely programmed velocity changes even if constant deceleration is not employed, and this requirement can overload the pilot without additional information to help him perform the changes.

For the X-22A application, determination of a configuration change command is relatively straightforward, since conversion consists simply of rotating the ducts toward the vertical and is controlled by a single "ON-OFF" button which commands a constant rotation rate (5 degrees/sec). Similar simplicity exists for the CL-84 (Reference 16) or the Harrier (e.g. Reference 21); although aircraft which employ auxiliary lift engines such as the DO-31 (Reference 29) require additional controllers, the overall concept is still applicable. The Independent Thrust Vector Inclination Command (ITVIC) developed for this experiment should therefore not be considered as specialized to the X-22A in concept, although the details of the implementation are, of course, related to only this aircraft's aerodynamic characteristics. The details of the command are described below, while those of the director are discussed in Section VI.

4.4.2 ITVIC Implementation

Figure 4-6 shows an approximate transition corridor of allowable velocity/duct angle combinations for the X-22A. As is shown in the figure, the center of this corridor can be fairly well approximated by a straight line, a circumstance which obviates the need to use a function generator but is not a general requirement. The equation for this line in terms of commanded duct angle as a function of commanded range rate is written as:

$$\lambda_c - 15 = .44 \left[\dot{X}_{e_c}(\hat{X}_e) + 170 \right] \tag{4-21}$$

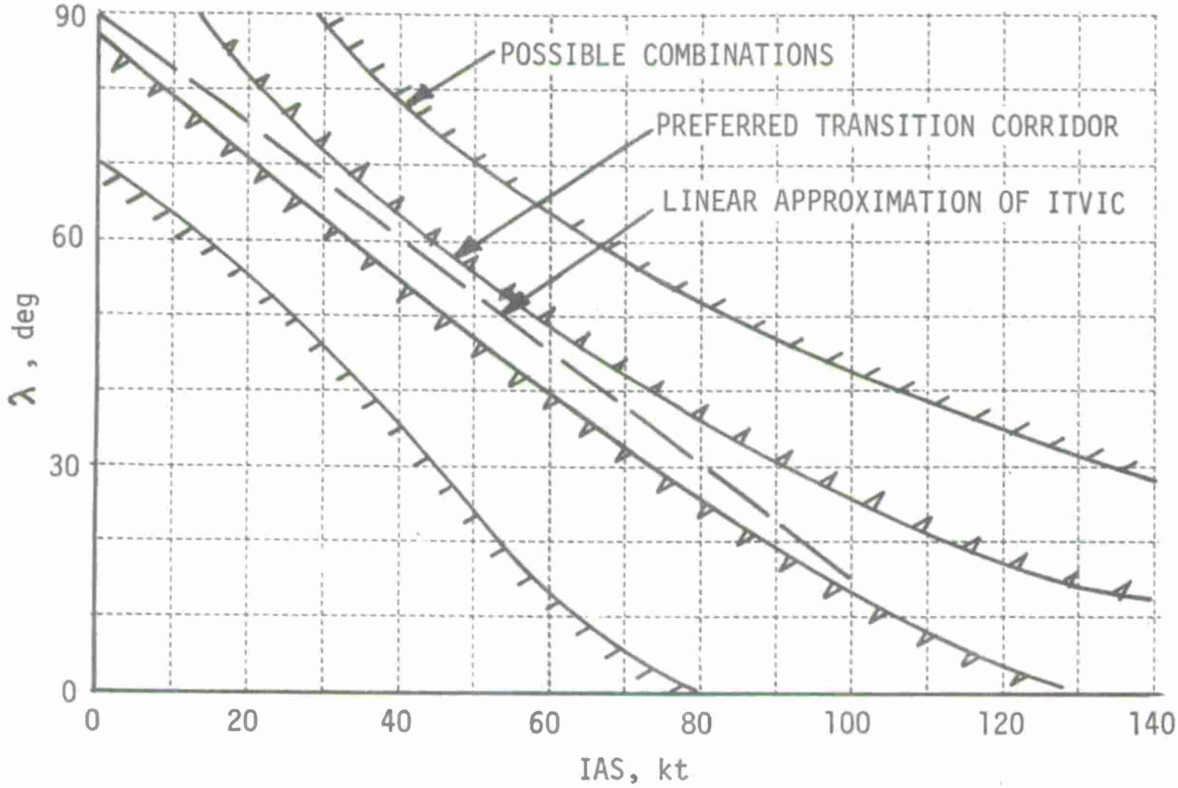


Figure 4-6 X-22A TRANSITION CORRIDOR

This equation represents the zero-wind relationship between commanded duct angle and range rate, and would start requiring duct rotation at the zero-wind deceleration initiation point.

Since the velocity command logic reviewed in Section 4.3 results in the range at which the commanded deceleration commences being variable dependent on headwind, implementation of Equation 4-21 would have been incorrect. The object was to begin the duct rotation commands coincident with the switch in command logic to the deceleration commands, maintaining the same relationship between changes in commanded duct angle and changes in commanded range rate. To effect such an implementation, a balance-and-hold circuit was used on the duct angle error signal ($\lambda - \lambda_c$): during the acquisition ("before switching") part of the approach, the circuit balanced the error signal, thereby forcing the duct angle command to remain effectively at the value of initial duct angle (λ = 15 degrees); at the switching point, the circuit switched to "hold" for the second part of the approach, thereby allowing computation of the error to begin based on the value of $\dot{X}_{ec}$ at the switching point rather than the zero-wind deceleration initiation point.

The effect of this logic on the duct angle command is shown in Figure 4-7 for the same 20 Kt headwind example used in Section 4.3.3. By virtue of the balance-and-hold circuit, the effective value of λ_c is forced to be 15 degrees until the switch point. When switching occurs, the duct angle command increases parallel to the zero-wind command, since the relationship between changes in duct angle and velocity is kept the same. As a result, the final commanded duct angle for zero ground speed is only 75 degrees for this example, which is approximately the correct angle for 20 Kt airspeed from Figure 4-6.

As can be seen from the example, this implementation of the duct angle command signal means that (1) the initiation of conversion from forward flight configuration ($\lambda = 15^{\circ}$) is coincident with the velocity logic switching at ranges which vary according to headwind, and (2) the final duct angle at hover will vary also, since the conversion rate is the same for all situations (same deceleration required). The airspeed/configuration (duct angle) relationship is therefore always maintained according to the reference combination. The use of this command in control system concepts requiring automatic configuration changes is discussed in Section V, and its application to the ITVIC duct angle director is described in Section VI.

4.5 VERTICAL-PLANE COMMANDS

A general requirement in the guidance relationships for decelerating descending approaches is that commands for both vertical position (glide slope) and vertical velocity be provided. In applications where only a control director display is considered, these commands are generally combined for display as one signal (e.g. References 5, 9). If, however, status information is needed for the display, errors computed from both commands may be required: an example is the initial FLEXIHUD format used in the CL-84 experiment (Reference 16), which did not include glide slope position information and

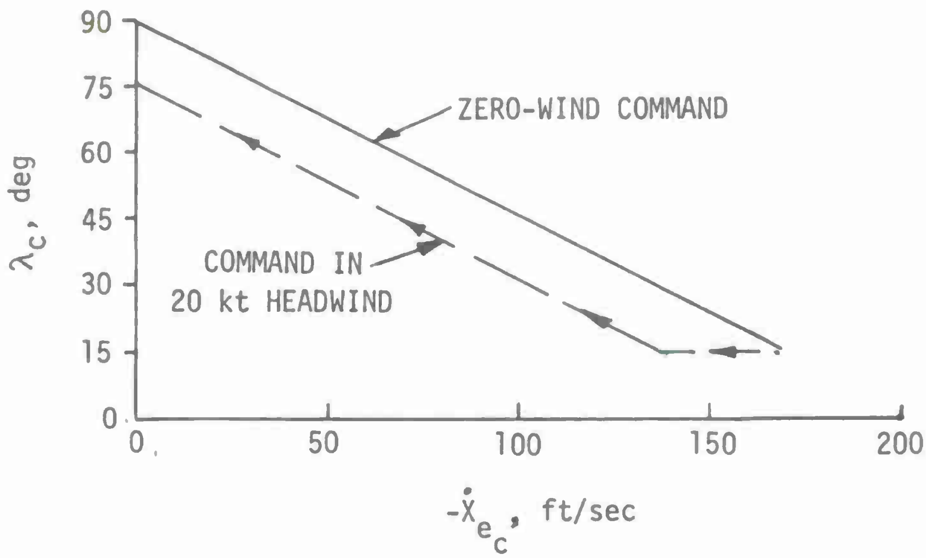
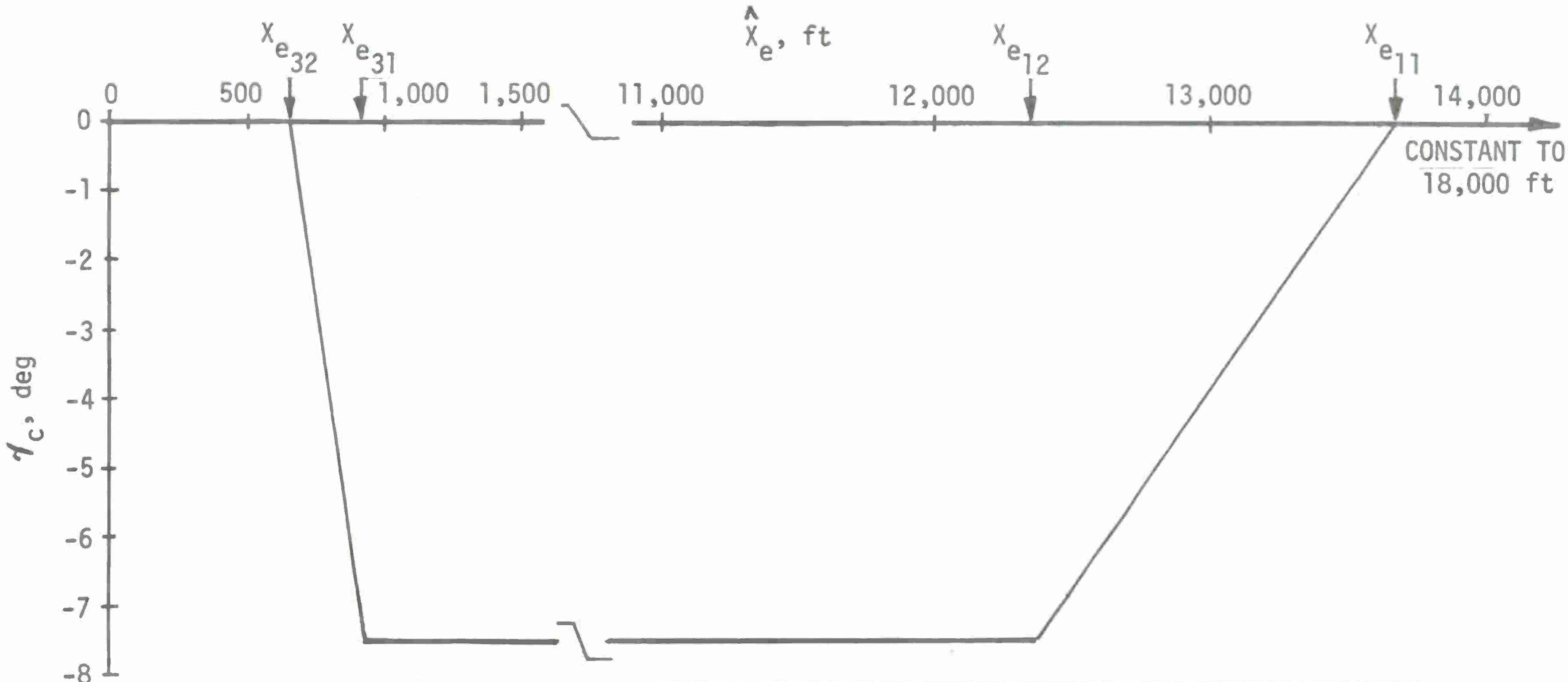


Figure 4-7 EFFECT OF HEADWIND ON ITVIC

led to unacceptable approach performance. Since this X-22A experiment considered both status and director displays, separate signals for the two commands were developed.

The geometry of the approach trajectory was summarized in Section III of this report, and consists essentially of level flight at 1700 feet AGL followed by a -7.5 degree descent to level off at 100 feet AGL. In order to reduce the difficulty of both the glide slope acquisition and level-off portions of this task, a commanded glide slope angle (γ_c) was used which provided a continuous angle change at these points rather than sharp "corners". The logic involved assuming a change in commanded angle of ± 1 deg/sec during acquisition and flare, which resulted in a total of 7.5 seconds for the total angle change, and assuming approximately constant velocity for each maneuver. On this basis, ranges at which commencement and conclusion of each maneuver occurred could be computed, and hence a functional dependence of γ_c derived. The resulting function is shown in Figure 4-8.

Figure 4-9 gives the vertical position and rate commands as a function of range that result from γ_c . Note that the vertical rate command ($\dot{z}_{e_c}$) is based on actual range rate ($\hat{\dot{x}}_e$) and not commanded range rate ($\dot{x}_{e_c}$); this choice was made to ensure that aircraft rate-of-descent limits would not be exceeded if poor deceleration tracking occurred. As can be seen from the figure, the position command (z_{e_c}) is not the same function of γ_c for all ranges, whereas ($\dot{z}_{e_c}$) is; therefore, the implementation consisted of a function generator for z_{e_c} approximating Figure 4-9, and another function generator approximating Figure 4-8 (γ_c) which was multiplied by $\hat{\dot{x}}_e$ to form $\dot{z}_{e_c}$.



	$\hat{X}_e > X_{e_{11}}$	$X_{e_{12}} < \hat{X}_e < X_{e_{11}}$	$X_{e_{31}} < \hat{X}_e < X_{e_{12}}$	$X_{e_{32}} < \hat{X}_e < X_{e_{31}}$	$\hat{X}_e < X_{e_{32}}$
γ_c	0	$+\dfrac{\hat{X}_e - X_{e_{11}}}{170}$	-7.5	$-\dfrac{\hat{X}_e - X_{e_{32}}}{52}$	0

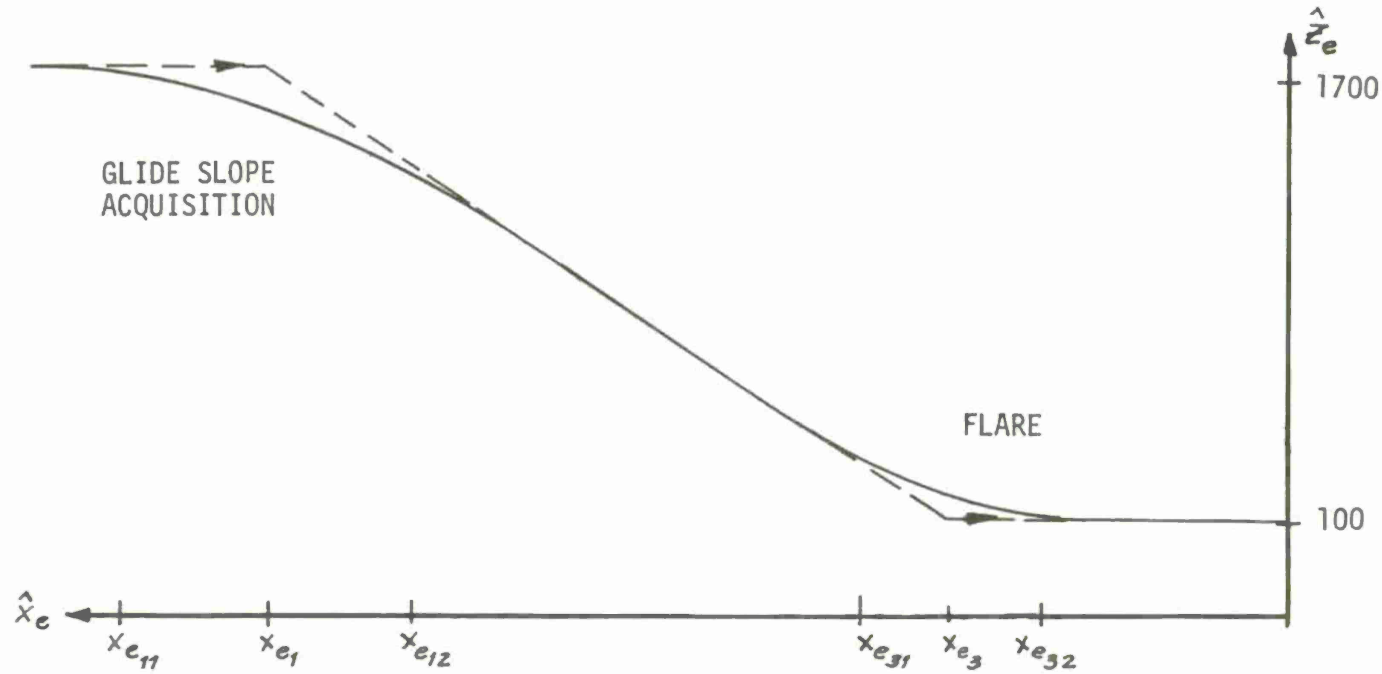
$$X_{e_{11}} = 13{,}000 - (3.75)(-170) = 13{,}637$$

$$X_{e_{12}} = 13{,}000 + (3.75)(-170) = 12{,}363$$

$$X_{e_{31}} = 760 - (3.75)(-\ 52) = 950$$

$$X_{e_{32}} = 760 + (3.75)(-\ 52) = 650$$

Figure 4-8 GLIDE SLOPE ANGLE COMMAND



COMMAND VALUES	$\hat{x}_e > x_{e_{11}}$	$x_{e_{11}} \ge \hat{x}_e > x_{e_{12}}$	$x_{e_{12}} \ge \hat{x}_e > x_{e_{31}}$	$x_{e_{31}} \ge \hat{x}_e > x_{e_{32}}$	$\hat{x}_e \le x_{e_{32}}$
$\dot{z}_{e_c}$	0	$-\hat{\dot{x}}_e \tan \gamma_c$	$-\hat{\dot{x}}_e \tan \gamma_c$	$-\hat{\dot{x}}_e \tan \gamma_c$	0
z_{e_c}	1700	$1700-\left(\frac{\hat{x}_e - x_{e_{11}}}{2}\right)\tan\gamma_c$	$-\hat{x}_e \tan \gamma_c$	$100-\left(\frac{\hat{x}_e - x_{e_{32}}}{2}\right)\tan\gamma_c$	-100
γ_c	0	$-\left(\frac{\hat{x}_e - x_{e_{11}}}{\dot{x}_{e_0}}\right)$	$-7.5°$	$\frac{\hat{x}_e - x_{e_{32}}}{\dot{x}_{e_3}}$	0

where $x_{e_{12}} = x_{e_1} + 3.75\,\dot{x}_{e_0}$

and $x_{e_{31}} = x_{e_3} - 3.75\,\dot{x}_{e_3}$

Figure 4-9 VERTICAL-PLANE COMMAND SUMMARY

Section V

CONTROL SYSTEMS DESIGN

5.1 SYNOPSIS OF SECTION

The purpose of this section is to describe the implementation of the five control system concepts investigated as one of the major variables in this experiment, and to define the resulting dynamic characteristics of the aircraft. The emphasis of the discussion will be on the dynamic characteristics in hover and at 100 Kt, since these conditions are at fixed operating points; the characteristics at a mid-transition fixed operating point (λ = 50 deg, V_o = 65 Kt) will also be summarized to indicate the trends in the dynamics, but it is emphasized that the actual dynamics in the decelerating transition as the airplane passes through this flight condition will be somewhat different because of the time-varying effects.

It is also emphasized that the dynamic characteristics discussed in this section are those actually achieved in flight as opposed to design values. Identification of these characteristics from flight data is performed using a technique developed by Calspan for the X-22A (Reference 30) which has been extensively applied to X-22A flight data in the past (References 31, 32); the details of the identification process for this experiment are given in Appendix IV. The design of the control system gains was based on approximate values of the X-22A stability and control derivatives as implemented in the X-22A ground simulator (Reference 12), and some differences exist between the aircraft and simulator characteristics; for this reason, presentation of the design value dynamic characteristics is eschewed in favor of those actually evaluated.

The philosophy guiding the selection of control system concepts for investigation was based on providing designs that would be consistent with previous work in the area of VTOL instrument landing approaches (see Section II of this report) but that would also represent "good" designs in the context of aircraft flying qualities. Toward this end, the requirements given in MIL-F-83300: Military Specification -- Flying Qualities of Piloted V/STOL Aircraft (Reference 4) were used as design criteria where possible, although compromises to reproduce the designs used in previous work were made if necessary. This program was conducted as a flying qualities experiment in which the intent was to provide the pilot with aircraft response characteristics that were as favorable as possible for each control system type so that the differences in type of augmentation would be emphasized; a comparison of the implemented characteristics with the applicable requirements of MIL-F-83300 is therefore included in this section. The next five subsections describe the designs and major characteristics of the five control systems considered, while the final subsection discusses the comparisons with selected MIL-83300 requirements considered to be of primary applicability.

5.2 RATE AUGMENTATION SYSTEM

The stability/control augmentation system of the simplest type considered feasible for V/STOL aircraft consists of only angular rate augmentation about all three axes. Although previous investigations of V/STOL instrument approaches assume a minimum complexity which includes angular attitude augmentation in addition to rate (e.g., References 5, 9, 12, 14), nonetheless many currently extant VTOL aircraft use only a rate damping system (e.g. AV-8A). Therefore, in order to investigate the efficacy of display information improvements on increasing the capabilities of such aircraft to perform the instrument decelerating descending transition, a rate SAS augmentation system representative of V/STOL aircraft was simulated on the X-22A.

In particular, the system was mechanized with pitch, roll, and yaw rate stabilization approximately equal to the basic X-22A SAS hover characteristics. The pilot was required to perform the duct rotation (configuration change) manually during the decelerating transition. A schematic diagram of the implementation is given in Figure 5-1, with the magnitudes of the gains listed; Appendix I lists all of the resulting aircraft transfer functions, at three duct angles, and Appendix II contains frequency response plots and selected time history responses. For the purposes of this discussion, only selected features of the characteristic dynamics will be reviewed.

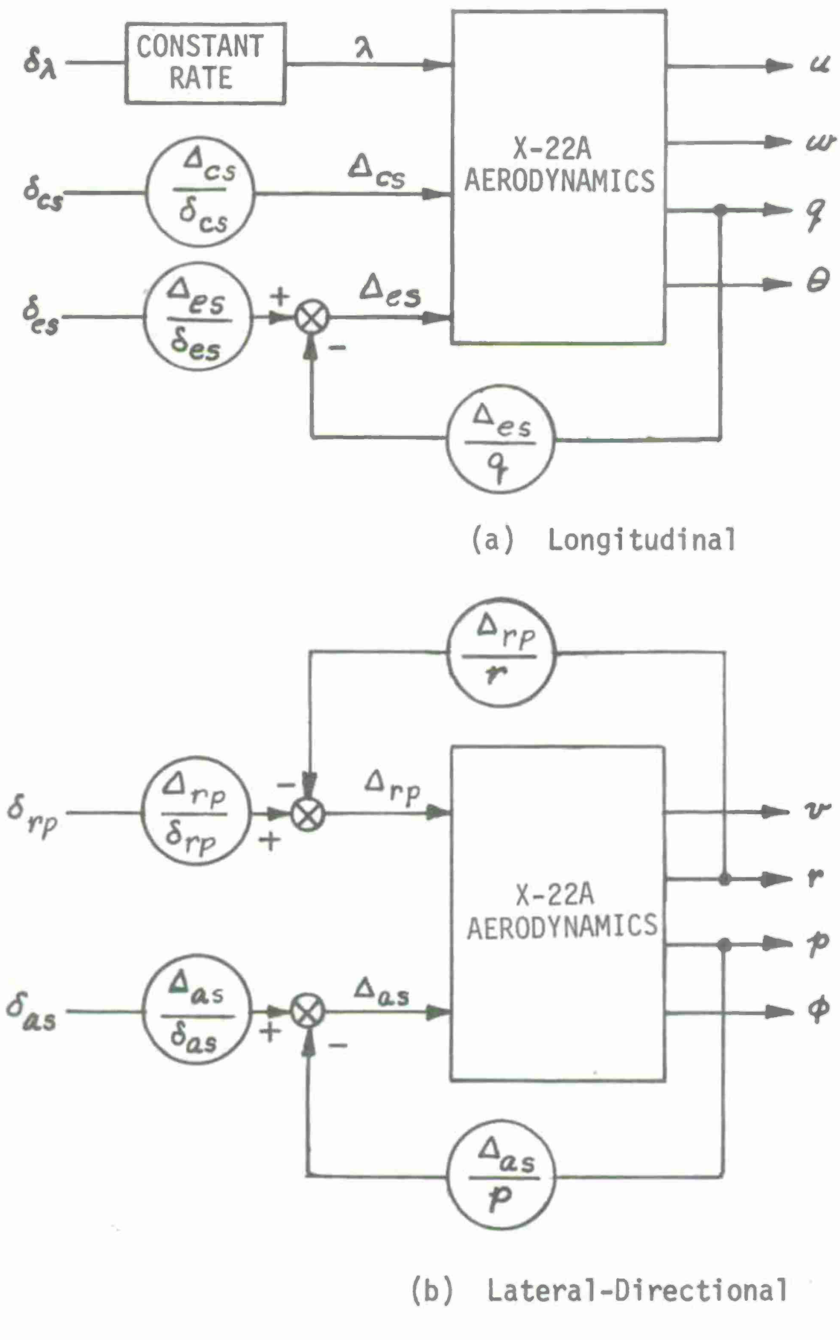
The longitudinal and lateral-directional characteristic equations are summarized below in Table 5-1:

Table 5-1

RATE AUGMENTATION CHARACTERISTIC EQUATIONS IN FORM $K(1/\tau)[\zeta;\omega_n]$

	LONGITUDINAL	LATERAL-DIRECTIONAL
0 Kt	$(.12)(2.94)[.10;.405]$	$(1.62)(2.71)[-.025;.45]$
65 Kt	$(-.09)(.176)[.94;1.95]$	$(.73)(3.04)[.59;.81]$
100 Kt	$(.93)(2.89)(.31)(-.12)$	$(.14)(3.14)[.42;1.35]$

In hover, the aircraft exhibits characteristics typical of VTOL aircraft: the longitudinal modes consist of an uncoupled vertical root (s = -.12), a well-damped pitch rate root (s = -2.94), and a lightly damped low frequency oscillation; the lateral modes consist of a yaw rate root (s = -1.62), roll rate root (s = -2.71), and a slightly unstable low frequency oscillation. At the glide slope acquisition speed (100 Kt), the characteristics are airplane-like: the longitudinal modes are dominated by an over-damped short period and an unstable



$\Delta_{es}/q = 8.9$

$\Delta_{es}/\delta_{es} = 1.25$

$\Delta_{cs}/\delta_{cs} = 1.25$

$\Delta_{rp}/r = 7.9$

$\Delta_{as}/p = 6.28$

$\Delta_{rp}/\delta_{rp} = 1.00$

$\Delta_{as}/\delta_{as} = 1.01$

Figure 5-1 IMPLEMENTATION OF RATE AUGMENTATION SYSTEM

aperiodic root caused by the negative speed stability (M_u); the lateral modes demonstrate a stable Dutch roll of moderate frequency and a rapid roll response mode (s = -3.14).

The characteristics may be considered representative of VTOL aircraft with rate SAS augmentation subject to the following cautions:

- The time constant of the angular rate responses are faster in hover than in some existing aircraft (e.g. AV-8A). These good response dynamics are achievable because of the high control powers of the X-22A in hover, and were selected to ensure Level 1 characteristics for this system (see Section 5.7).

- The response characteristics during the transition are dependent on the X-22A aerodynamic characteristics and hence not completely general. It is noted, however, that the longitudinal aerodynamics are representative of VTOL aircraft which rotate aerodynamic surfaces during the conversion (tilt duct, tilt wing).

- The low vertical damping in hover is typical of VTOL aircraft with high disk loading or jet lift, but is lower than that for helicopters.

5.3 ATTITUDE COMMAND AUGMENTATION

This control system is the baseline configuration chosen to be similar in concept to that used in the NASA VALT experiments (Reference 5); it and the attitude/rate system to be discussed in the next subsection represent the prevalent opinions on the type of control augmentation that is the minimum necessary to perform decelerating instrument approaches and/or hover (References 5, 9, 13, 20). In general, feedback of pitch and roll attitude as well as rate has been considered to be necessary for at least the following reasons:

- Stabilization of the oscillatory roots that are typical in hover.

- Reduction of pitching moments due to thrust vector magnitude and direction changes during transition.

- Feedback of some pitch and roll attitude information to the pilot through the control stick forces for the instrument hover.

In addition to pitch and roll attitude stabilization, directional augmentation more complex than yaw rate damping has been deemed necessary. References 13 and 20 indicate a requirement for increased weathercock stability in transition, while most research has indicated a need for rate-command-heading-hold in the hover; the NASA VALT experiments therefore provided a dual-mode directional system to meet these directional requirements (Reference 5).

The attitude command system investigated in this experiment was therefore implemented to provide the following responses:

- Pitch: attitude commanded by longitudinal stick, approximately 0.1 rad/inch
- Roll: attitude commanded by lateral stick, approximately 0.2 rad/inch
- Yaw: either zero-sideslip turn following (sideslip commanded by rudder pedals, approximately 8 ft/sec/inch at 100 Kt) or rate-command-attitude hold (yaw rate commanded by rudder pedals, approximately 0.25 rad/sec/inch); mode selectable by pilot.

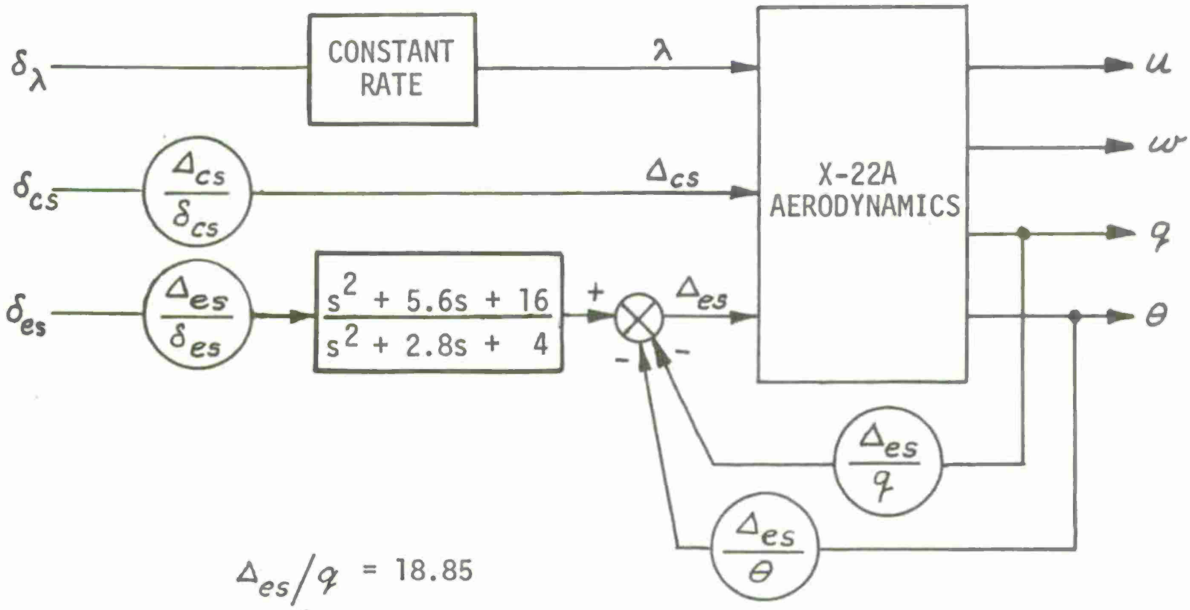
A schematic diagram of the implementation, including the feedback and feed-forward gains, is given in Figure 5-2; again, Appendices I and II should be referred to for details. A general discussion of the characteristics in each axis is given below.

As can be seen from Figure 5-2, the pitch axis uses high values of pitch rate and attitude stabilization plus command shaping through a second-order prefilter "model". The high level of augmentation is used to minimize turbulence response and coupling inputs to pitch attitude from the collective stick (thrust magnitude) and duct rotation (thrust direction) as well as to reduce the effect of the changing aerodynamic characteristics during transition on the pitch attitude response. The pitch stick command shaping is used to provide satisfactory (e.g. less abrupt) responses to control inputs, with the characteristics of the prefilter chosen to ensure "good" short-term dynamic characteristics as determined in an earlier X-22A experiment (Reference 10); note in particular that the implementation is similar to model-following practices in that feedforward gains are used to maintain a second-order aircraft response. The efficacy of this system in providing attitude responses that do not vary greatly during transition may be seen by considering the pitch-to-longitudinal-stick transfer functions in Table 5-2:

Table 5-2

PITCH ATTITUDE TO LONGITUDINAL STICK TRANSFER FUNCTIONS
ATTITUDE COMMAND SYSTEM

100 Kt	$\frac{[.7\,;\,4.0]}{[.7\,;\,2.0]} \cdot \frac{.38\,(.24)(.58)}{(.23)(.55)[.76\,;\,4.1]}$
65 Kt	$\frac{[.7\,;\,4.0]}{[.7\,;\,2.0]} \cdot \frac{.41\,(.17)(.58)}{(.17)(.50)[.72\,;\,4.45]}$
0 Kt	$\frac{[.7\,;\,4.0]}{[.7\,;\,2.0]} \cdot \frac{.44\,(.12)(.14)}{(.12)(.14)[.74\,;\,4.29]}$



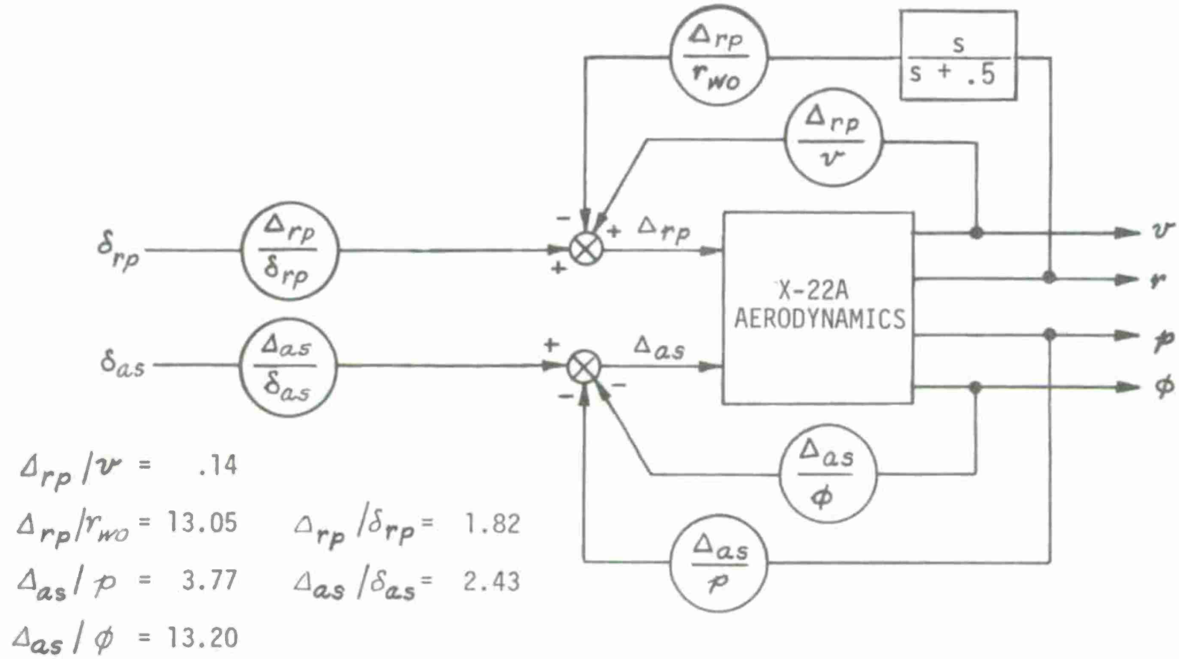
$$\Delta_{es}/q = 18.85$$

$$\Delta_{es}/\theta = 53.22$$

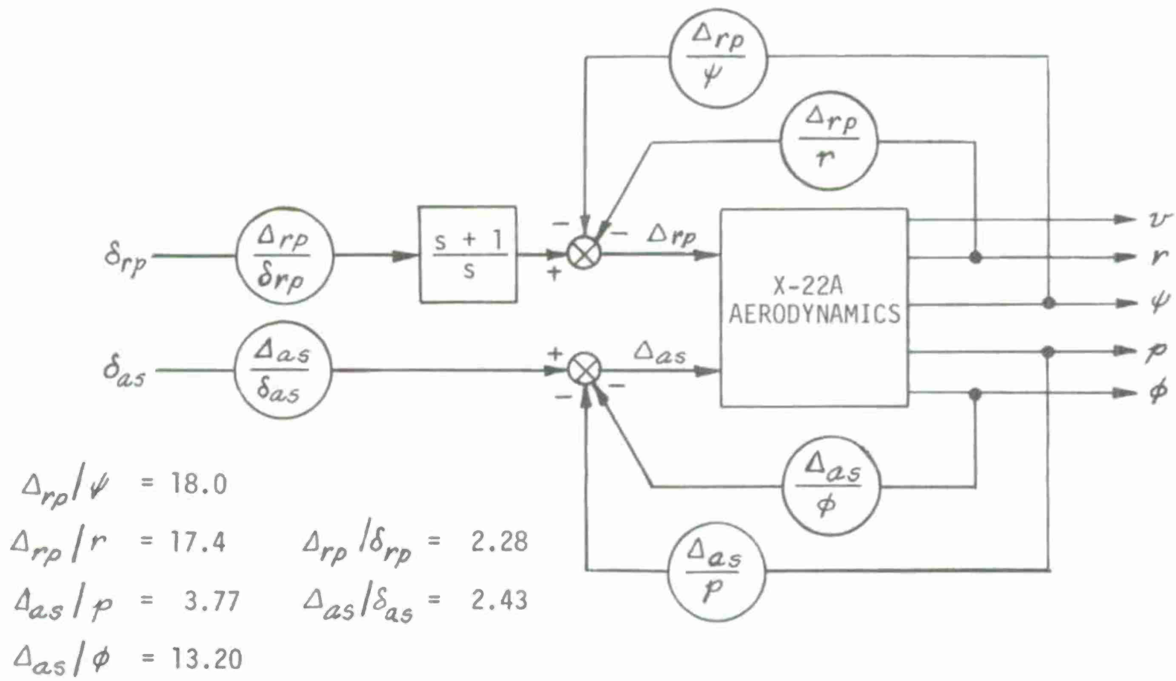
$$\Delta_{es}/\delta_{es} = 1.256$$

$$\Delta_{cs}/\delta_{cs} = 1.25$$

Figure 5-2a IMPLEMENTATION OF ATTITUDE COMMAND SYSTEM (LONGITUDINAL)



Turn-following (ATC)



Heading-hold (HH)

Figure 5-2b IMPLEMENTATION OF ATTITUDE COMMAND SYSTEM (LATERAL-DIRECTIONAL)

In the lateral channel, a similar implementation was precluded because of limitations in allowable roll rate feedback caused by noise in the roll rate gyro signal; this limitation meant that a well-damped highly attitude-augmented system could not be achieved. To provide symmetric longitudinal and lateral attitude response characteristics in the hover, the implementation therefore consisted of roll rate and attitude augmentation at a level sufficient to produce a natural frequency of approximately 2 rad/sec, which is the "model" natural frequency in the pitch channel. The lateral-directional characteristics are further modified by the directional augmentation system. In the turn-following mode (ATC), which is designed to improve the forward flight characteristics, the Dutch roll frequency and damping ratio are increased by feeding back lateral air velocity and washed-out yaw rate; the X-22A is similar to most VTOL aircraft in exhibiting poor directional stability during the transition, and this implementation, which is similar to that used in the NASA VALT program (Reference 5), is designed to reduce the amount of attention the pilot must devote to sideslip control, as was recommended in Reference 13 and 20. The heading-hold mode (HH) is directed at the hover, and uses feedback of heading and yaw rate to achieve heading stabilization with a natural frequency of approximately 2 rad/sec that is slightly overdamped; an integral-plus-proportional prefilter is used on the rudder pedal commands to provide yaw-rate-command-heading-hold response characteristics. The roll attitude response to a lateral stick command is summarized in Table 5-3 assuming the ATC mode selected for 100 Kt and 65 Kt and the HH mode for hover:

Table 5-3

ROLL ATTITUDE TO LATERAL STICK TRANSFER FUNCTIONS,

ATTITUDE COMMAND SYSTEM

100 Kt (ATC)	$\dfrac{.97(.55)[.51;1.61]}{(.52)[.74;1.41][.3;2.66]}$
65 Kt (ATC)	$\dfrac{.93(.73)[.89;1.48]}{(.49)[.96;1.63][.31;2.44]}$
0 Kt (HH)	$\dfrac{.97(1.83)(2.16)(.06)}{(1.70)(2.48)(.16)[.30;2.20]}$

To summarize, the attitude command system discussed here and the attitude/rate system to be discussed in the next subsection may be considered to be the first increases in control augmentation or automation over the basic rate augmentation system discussed in the last subsection, and in fact represent a realistic limit to control system improvements that may be achieved with angular augmentation. Again, the pilot is required to perform the duct rotation manually, and no translational velocity augmentation (e.g. height damping) is included.

5.4 ATTITUDE/RATE COMMAND AUGMENTATION

The emphasis of this experiment was on localizer and glide slope tracking through the deceleration and hover, for which it was hypothesized that attitude command in pitch and roll would be desirable. Nonetheless, it is a well recognized fact that roll attitude command is generally disliked by pilots for gross maneuvering during up and away flight and localizer acquisition because of the necessity to hold a constant force while performing a turn. For this reason, one approach to control system design is to provide attitude augmentation in pitch but only rate augmentation in roll; the CL-84 control system is an example of this philosophy (Reference 16). In order to ascertain whether or not increases in display sophistication would be required to perform the instrument deceleration and hover satisfactorily when roll rate command was provided rather than roll attitude command, therefore, a control system which provided attitude command in pitch but rate-command-attitude-hold in roll was included for investigation.

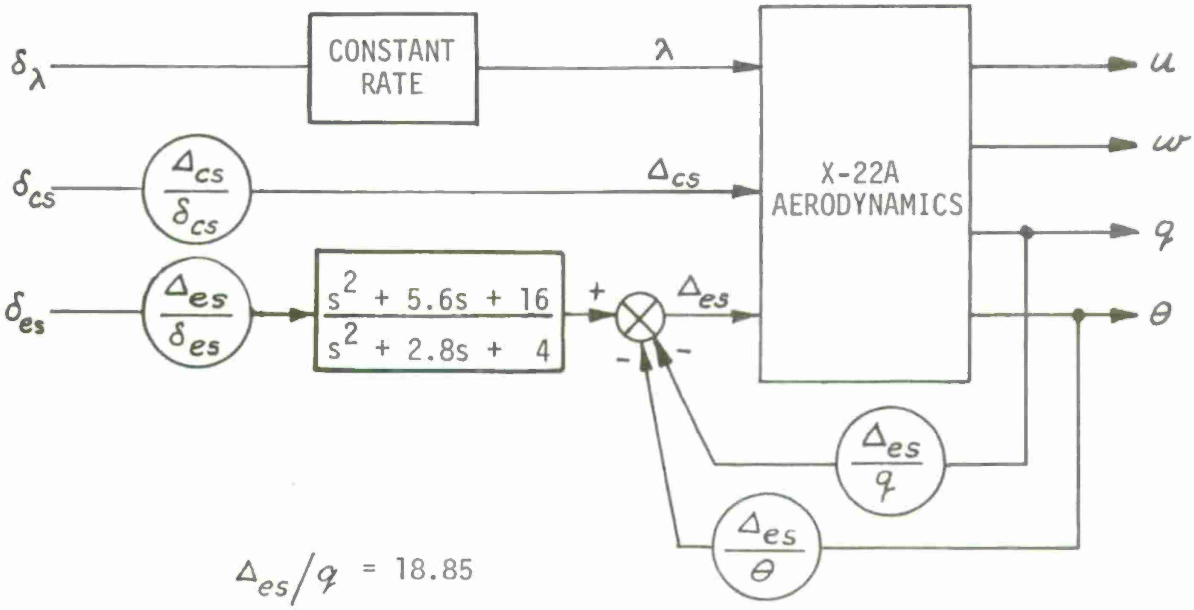
The implementation of this attitude/rate command system is shown in Figure 5-3. As can be seen from the figure, this system is identical to the attitude command system (Section 5.3) in the pitch and yaw channels. The roll axis uses the same amount of roll attitude feedback, but has increased roll rate feedback and a proportional-plus-integral command prefilter with a lead time constant of 0.5 seconds. This implementation had the intent of achieving close to critical damping (ζ = 1.0) of the 2 rad/sec attitude augmented roots so that the roll rate response resulting from a stick input would have a time constant of 0.5 seconds, which was a value selected to be "good" from an earlier X-22A experiment (Reference 11); as the roll attitude transfer functions in Table 5-4 show, this desideratum was not achieved exactly, but the placement of the prefilter zero with respect to the attitude poles still does result in a rapid well damped roll rate response.

Table 5-4

ROLL ATTITUDE TO LATERAL STICK TRANSFER FUNCTIONS

ATTITUDE/RATE COMMAND SYSTEM

100 Kt (ATC)	$\dfrac{.40(2)(.55)[.51;\ 1.61]}{(0)(.52)[.44;\ 2.53][.83;\ 1.49]}$
65 Kt (ATC)	$\dfrac{.385(2)(.73)[.89;\ 1.48]}{(0)(.48)[.48;\ 2.38][.97;\ 1.70]}$
0 Kt (HH)	$\dfrac{.40(2)(2.61)(1.83)(.060)}{(0)(2.60)(1.67(.17)[.52;\ 2.15]}$



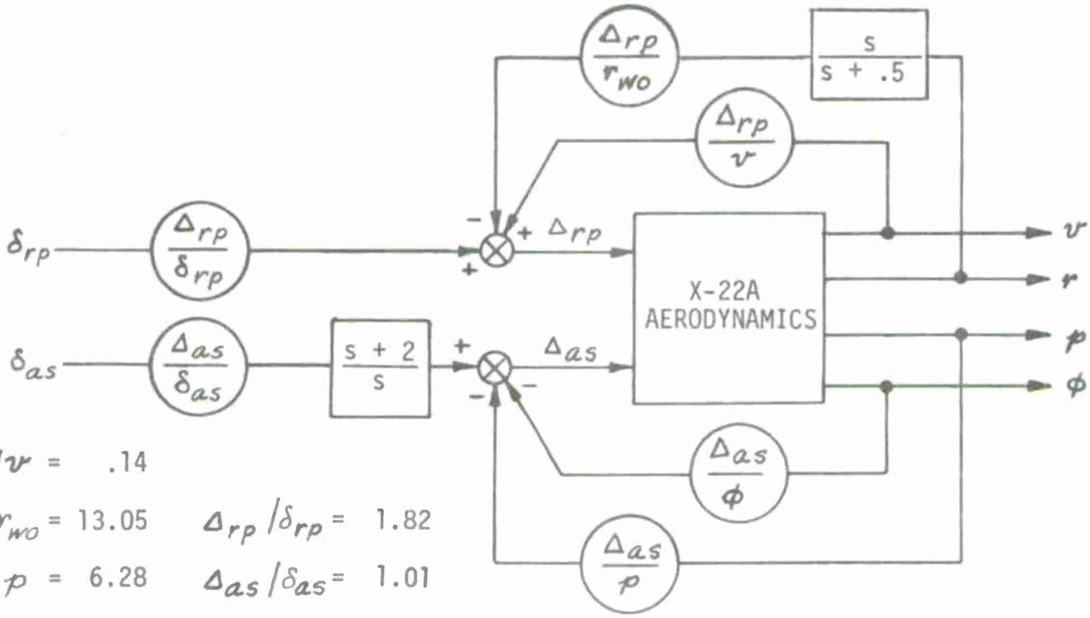
$\Delta_{es}/q = 18.85$

$\Delta_{es}/\theta = 53.22$

$\Delta_{es}/\delta_{es} = 1.256$

$\Delta_{cs}/\delta_{cs} = 1.25$

Figure 5-3a IMPLEMENTATION OF ATTITUDE/RATE COMMAND SYSTEM (LONGITUDINAL)



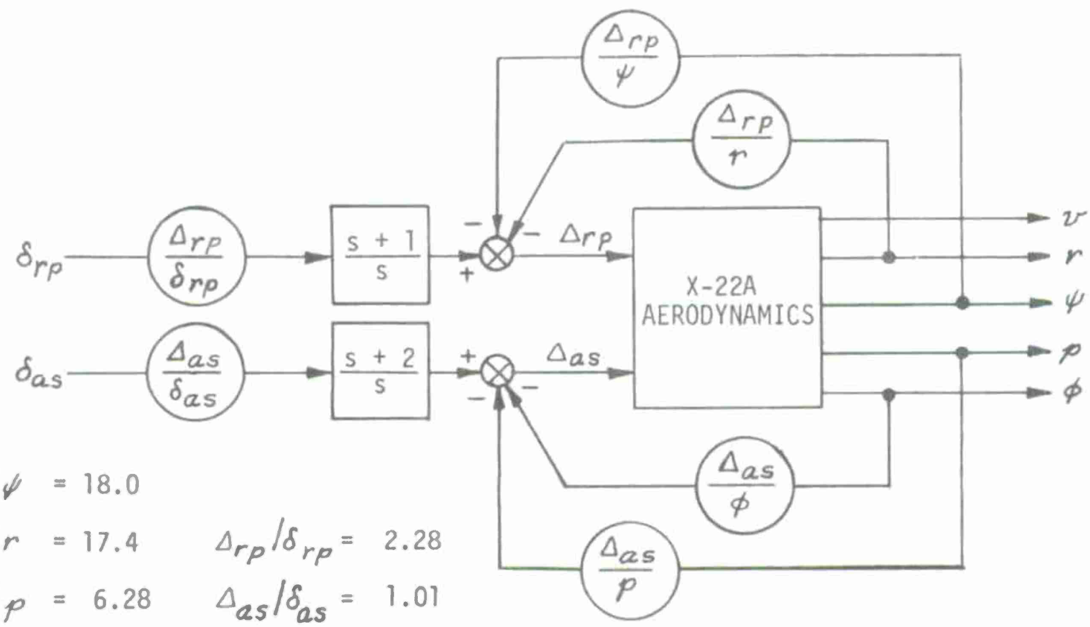
Δ_{rp}/v = .14

Δ_{rp}/r_{wo} = 13.05 Δ_{rp}/δ_{rp} = 1.82

Δ_{as}/p = 6.28 Δ_{as}/δ_{as} = 1.01

Δ_{as}/ϕ = 13.20

Turn-following (ATC)



Δ_{rp}/ψ = 18.0

Δ_{rp}/r = 17.4 Δ_{rp}/δ_{rp} = 2.28

Δ_{as}/p = 6.28 Δ_{as}/δ_{as} = 1.01

Δ_{as}/ϕ = 13.20

Heading-hold (HH)

Figure 5-3b IMPLEMENTATION OF ATTITUDE/RATE COMMAND SYSTEM (LATERAL-DIRECTIONAL)

In summary, the following points concerning the attitude/rate system as implemented are noted:

- As with the attitude command system, duct rotation is manual and no augmentation of translational rates or positions is used. The only difference between the two systems is that roll attitude is commanded by lateral stick position with the attitude command system while the same input commands roll rate (with attitude hold for no input) in the attitude/rate command system.

- The implementation that was chosen used a command prefilter rather than methods which use an integrator in the forward loop after the summation of the command and feedback signals. In general, this method of mechanization should include a dead-zone prior to the feedforward integrator to aid trimming the aircraft; system limitations precluded the inclusion of the dead-zone in this implementation.

- An alternate roll control system proposed in Reference 13 is to command roll attitude for small lateral stick inputs and roll rate for large ones. This type of system appears desirable in principle, but it is unclear at what roll attitude the switch in command should occur and what tailoring of the dynamic characteristics is required to provide a satisfactory switch. In any case, it is likely that the localizer tracking after acquisition would generally consist of small and hence attitude command inputs, and the effects of such a system on system performance are therefore essentially given by the attitude command system considered in this experiment.

5.5 AUTOMATIC DUCT ROTATION

As has been discussed (Sections 1.1, 4.4), the pilot's control problems in performing decelerating transitions with VTOL configurations different than the helicopter have an added dimension because of the requirement to change the aircraft's configuration. This dimension results in at least one additional controller which must be manipulated in a precisely scheduled fashion if a specific deceleration profile is required. It is clear, therefore, that the first degree of automaticity to be considered would be the guidance coupling required to perform the configuration changes automatically.

The next type of increased control complexity investigated in this experiment therefore consisted of adding automatic duct rotation to the attitude command system discussed in Section 5.3. A schematic diagram of the

implementation is given in Figure 5-4; the transfer functions and time history responses are identical to those for the attitude command system, since no additional augmentation (e.g. height damping) is added. The duct rotation is commanded by comparing duct angle with the ITVIC guidance laws discussed in Section 4.4: the ducts rotate toward 90 degrees when this error ($\lambda_c - \lambda$) is greater than 3 degrees until it is reduced to 0.5 degrees. This value of hysteresis, which is also used for the ITVIC director discussed in Section VI, was selected both to reduce the number of pressure transients in the duct drive hydraulic system and to meet pilot-oriented requirements when the signal was used as a director (see Section VI).

To summarize, this control system represents an increase in complexity from the baseline attitude command system by relieving the pilot of the duct rotation function. All other characteristics of the control situation are identical to the attitude command system.

5.6 DECOUPLED VELOCITY CONTROL (DVC) SYSTEM

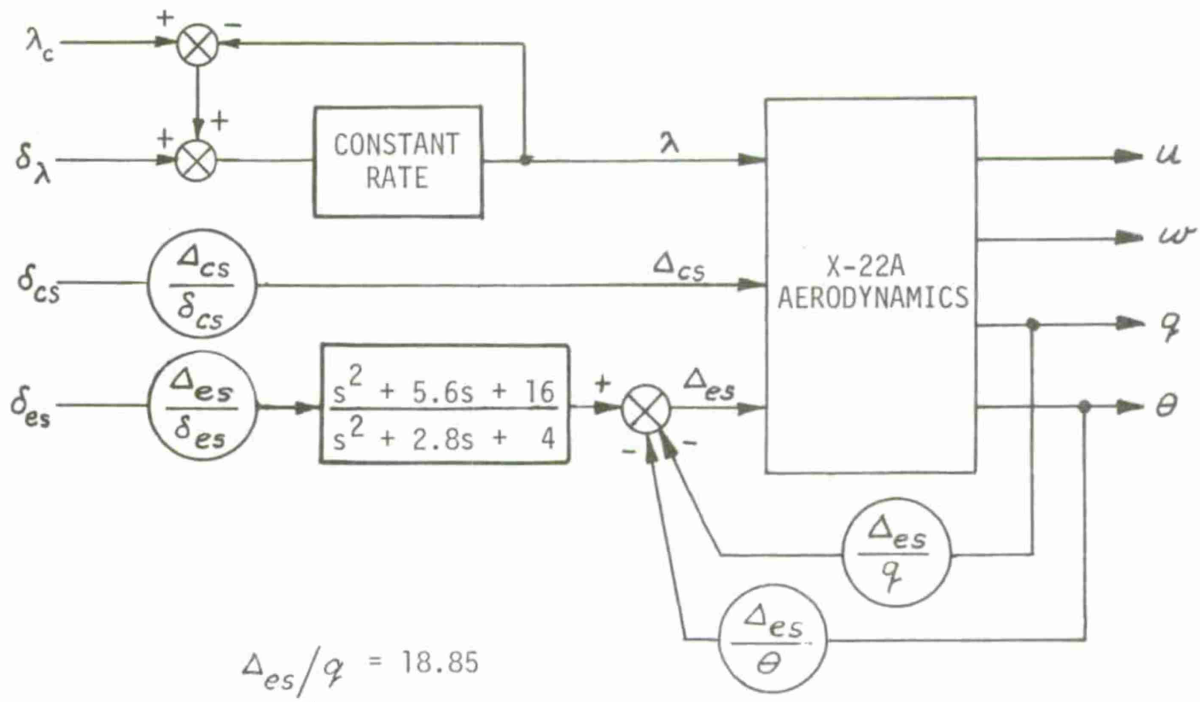
During the final portion of an instrument approach and particularly in the hover the pilot is interested in using longitudinal and lateral velocities to control his position with respect to the ground. For this reason, it has been considered desirable to provide him with direct, decoupled control of these velocities: Reference 13 describes the advantages of a "Cartesian" velocity control system, and an attempt to provide such a system for a helicopter has been investigated in the TAGS program (e.g. Reference 33). VTOL aircraft which have some control of thrust inclination independently of pitch attitude offer the capability to provide longitudinal velocity control directly without the attendant pitch motions required by helicopters, and this fact, combined with the possible requirements of decoupled control of vertical velocity and increased height damping for VTOL aircraft, formed the basis for the design of the most complex control augmentation system investigated in this experiment.

The intent of the design of the decoupled velocity control system was:

- To provide decoupled responses to collective stick (vertical velocity with respect to the ground) and duct angle (longitudinal velocity with respect to the ground) over the full range of duct angles from forward flight to hover.

- To provide augmented damping and hence improved aircraft responses in vertical and longitudinal velocity.

- To minimize pitch attitude input requirements through the transition.



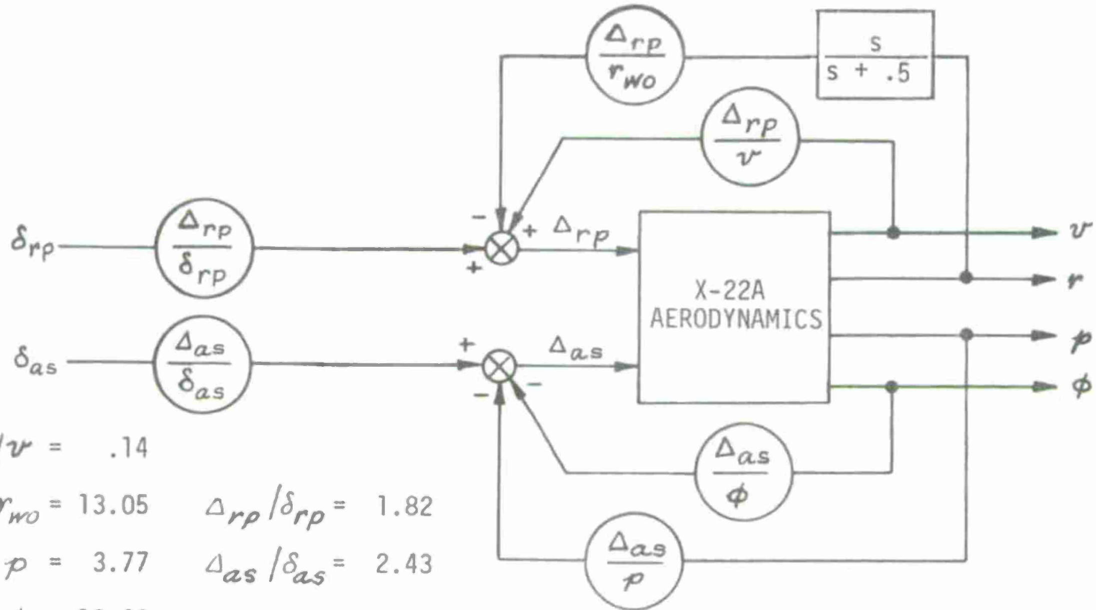
$\Delta_{es}/q = 18.85$

$\Delta_{es}/\theta = 53.22$

$\Delta_{es}/\delta_{es} = 1.256$

$\Delta_{cs}/\delta_{cs} = 1.25$

Figure 5-4a IMPLEMENTATION OF AUTOMATIC λ SYSTEM (LONGITUDINAL)



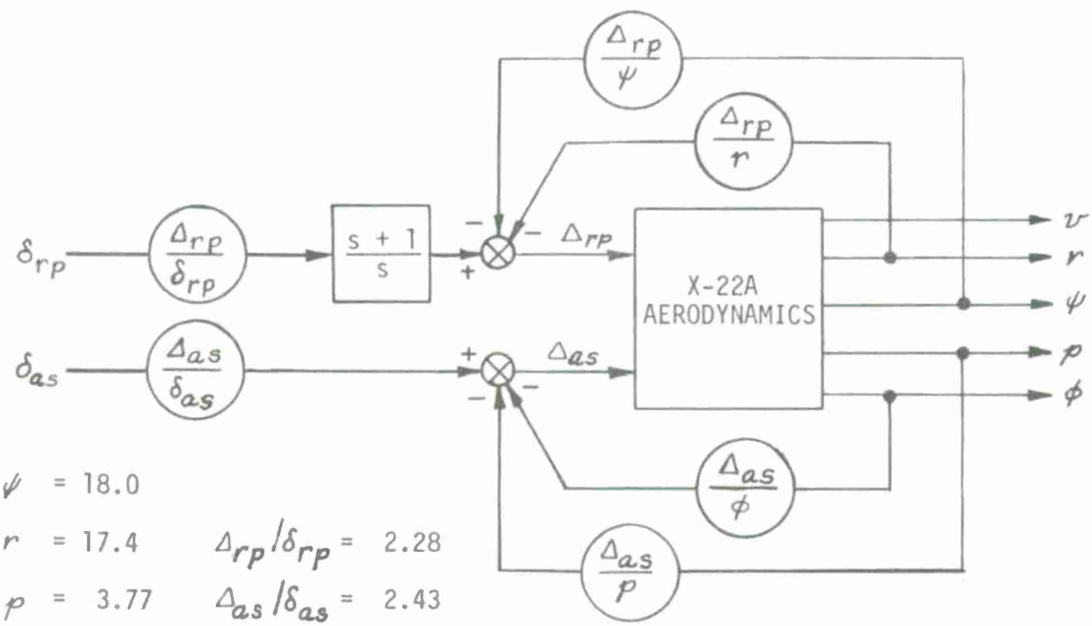
Δ_{rp}/v = .14

Δ_{rp}/r_{wo} = 13.05 Δ_{rp}/δ_{rp} = 1.82

Δ_{as}/p = 3.77 Δ_{as}/δ_{as} = 2.43

Δ_{as}/ϕ = 13.20

Turn-following (ATC)



Δ_{rp}/ψ = 18.0

Δ_{rp}/r = 17.4 Δ_{rp}/δ_{rp} = 2.28

Δ_{as}/p = 3.77 Δ_{as}/δ_{as} = 2.43

Δ_{as}/ϕ = 13.20

Heading-hold (HH)

Figure 5-4b IMPLEMENTATION OF AUTOMATIC λ SYSTEM (LATERAL-DIRECTIONAL)

In order to achieve improved velocity responses with respect to the ground, it is clear that the translational rate errors as determined by the guidance system (i.e. $\dot{X}_{e_c} - \hat{\dot{X}}_e$, $\dot{Z}_{e_c} - \hat{\dot{Z}}_e$ from Section IV) had to be used in addition to conventional aircraft quantities as feedback variables. This control system may therefore be considered as a guidance-coupled system longitudinally and vertically, and hence is only one step away from a fully automatic system. A summary of the design procedure is given below; Reference 34 is recommended for additional details.

The first step is to write the aircraft equations of motion in the axis system of the desired responses: that is, in terms of ground velocities ($\hat{\dot{X}}_e$ and $\hat{\dot{Z}}_e \triangleq \hat{\dot{h}}$). In addition, since duct rotation on the X-22A is controlled by an ON-OFF rate controller (± 5 deg/sec), it was decided to avoid using feedbacks to duct angle; the ITVIC error signal ($\Delta\lambda = \lambda_c - \lambda$) could, however, be used as a feedback variable, and so the equations are written with $\Delta\lambda$ as an additional state variable. Assuming that aircraft heading with respect to the desired course is nearly zero:

$$\begin{bmatrix} \hat{\ddot{X}}_e \\ \hat{\ddot{h}} \\ \dot{\theta} \\ \dot{q} \\ \Delta\dot{\lambda} \end{bmatrix} = \begin{bmatrix} X_u & X_w & g + w_0 X_u - u_0 X_w & 0 & -X_\lambda \\ Z_u & Z_w & w_0 Z_u - Z_w u_0 & 0 & -Z_\lambda \\ 0 & 0 & 0 & 1 & 0 \\ -M_u & -M_w & u_0 M_w - w_0 M_u & M_q & M_\lambda \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \hat{\dot{X}}_e \\ \hat{\dot{h}} \\ \theta \\ q \\ \Delta\lambda \end{bmatrix} + \begin{bmatrix} -X_{\Delta es} & -X_{\Delta cs} & 0 \\ -Z_{\Delta es} & -Z_{\Delta cs} & 0 \\ 0 & 0 & 0 \\ M_{\Delta es} & M_{\Delta cs} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta_{es} \\ \Delta_{cs} \\ \dot{\lambda} \end{bmatrix} \qquad (5\text{-}1)$$

or

$$\dot{\hat{y}} = \hat{F}\hat{y} + \hat{G}\hat{u}$$

The object is to find feedback gains and control cross-gearings to achieve augmented and decoupled responses. Hence, we may consider a model of the system as desired:

$$\begin{bmatrix} \hat{\ddot{X}}_e \\ \hat{\ddot{h}} \\ \dot{\theta} \\ \dot{q} \\ \Delta\dot{\lambda} \end{bmatrix} = \begin{bmatrix} -a_1 & 0 & 0 & 0 & a_2 \\ 0 & -a_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & -a_4 & -a_5 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \hat{\dot{X}}_e \\ \hat{\dot{h}} \\ \theta \\ q \\ \Delta\lambda \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & b_2 & 0 \\ 0 & 0 & 0 \\ b_3 & 0 & 0 \\ 0 & 0 & b_1 \end{bmatrix} \begin{bmatrix} \delta_{ES} \\ \delta_{CS} \\ \delta_\lambda \end{bmatrix} \qquad (5\text{-}2)$$

or

$$\dot{\hat{y}}_D = \hat{F}_D \hat{y}_D + \hat{G}_D \hat{w}$$

The selection of the desired values of the a_{ij} and b_{ij} was performed by assuming a "comfortable" pilot model consisting of a gain plus time delay closing each manual loop (see Reference 35 for an example of this technique applied to a different problem); the a_{ij} are then chosen to achieve acceptable closed loop stability and bandwidth, and the b_{ij} to achieve response-to-input sensitivities compatible with the appropriate MIL-F-83300 requirements (Reference 4). These selections are summarized below:

- $a_1 = 0.5$ (2 second time constant) This term is the time constant of the longitudinal velocity response to a duct angle change. Based on the closed loop results, the initial choice was 1.0 to achieve a closed loop frequency of $\omega_n = 1.0$ rad/sec with acceptable damping. The resulting gains in the feedbacks of longitudinal velocity and duct angle error to the collective and longitudinal sticks were found to cause unacceptable pitch oscillations during the transition when checked out on the ground simulator, and so the criterion was relaxed by a factor of two.

- $a_2 = 1.0$ The numerator of $\dot{x}_e/\delta_\lambda$ is $a_2 b_1$; the value of b_1 is fixed at 5 deg/sec by the X-22A rotation system. The MIL-F-83300 requirement on velocity response for the vertical axis (Requirement 3.2.5.3) is that:

  $$100 \leq \frac{\Delta \dot{h}}{\delta_{cs}} \leq 750 \quad \text{fpm/inch in one second}$$

  Assuming a similar magnitude longitudinally would be desirable (in the hover); picking 120 fpm/inch = 2 fps/inch gives $a_2 = \sim 1$ ft/sec^2/deg.

- $a_3 = 2.0$ (0.5 second time constant). This term is the vertical velocity response time constant, and is selected to provide good closed loop characteristics ($\omega_n \cong 1.5$, $\zeta \cong 0.35$).

- $a_4 = 6.25$ (2.5 rad/sec natural frequency). This term is the pitch attitude natural frequency, and was selected to provide good closed loop characteristics.

- $a_5 = 4.7$ (0.94 damping ratio). This term is the pitch attitude damping ratio, and is selected to reduce pitch oscillations found in the ground simulation checkout.

- b_1 = 5.0 This value is fixed by the existing X-22A duct rotation system.

- b_2 = 13.4 Using the MIL-F-83300 requirement again but picking 400 fpm = 6.7 fps for the steady state gives the value of 13.4; the response at one second is then 5.8 fps.

- b_3 = 0.4 The MIL-F-83300 requirement for pitch attitude response (3.2.3.2) is that:

  $$3 \leq \Delta\theta/\delta_{es} \leq 20 \text{ deg/inch in one second}$$

  This value was initially chosen as 0.25 rad/inch, giving b_3 = 1.6. Again, the attitude excursions found in the ground simulator checkout were unacceptable. In an attempt to minimize these excursions, the control sensitivity was reduced, thereby forcing the pilot to allow the stabilization system to perform the attitude regulation.

With the desired "model" characteristics defined, the next object is to solve for the control law which will approximate them in the aircraft. The general form of this law is:

$$\hat{u} = -K\hat{y} + J\hat{w} \tag{5-3}$$

K = Feedbacks

J = Control gearings and cross-feeds

$\hat{w}$ = $[\delta_{es}, \delta_{cs}, \delta_\lambda]^T$

$\hat{u}$ = $[\Delta_{es}, \Delta_{cs}, \dot{\lambda}]^T$

$\hat{y}$ = $[\dot{x}_e, \dot{h}, \theta, \dot{\theta}, \Delta\lambda]^T$

In particular, to avoid using feedbacks or cross-gearings to the duct angle controller, it is desired that:

$$K = \begin{bmatrix} K_{11} & K_{12} & K_{13} & K_{14} & K_{15} \\ K_{12} & K_{22} & K_{23} & K_{24} & K_{25} \\ \hline 0 & 0 & 0 & 0 & 0 \end{bmatrix} \triangleq \begin{bmatrix} K_2 \\ \hline 0 \end{bmatrix} \tag{5-4}$$

$$J = \begin{bmatrix} J_{11} & J_{12} & 0 \\ J_{21} & J_{22} & 0 \\ 0 & 0 & 5 \end{bmatrix} \triangleq \left[\begin{array}{cc|c} \multicolumn{2}{c|}{J_2} & \begin{matrix} 0 \\ 0 \end{matrix} \\ \hline 0 \; 0 & & 5 \end{array}\right]$$

The values of these gains were found as outlined below, using estimates for the aircraft characteristics at duct angles of 15, 30, 50, 70, and 90 degrees; these estimates were obtained from the ground simulator model and preliminary flight tests. It is emphasized that the duct angle derivatives ($M_\lambda, X_\lambda, Z_\lambda$) can not be easily or accurately identified from flight test because the nature of the controller ($\dot{\lambda} = \pm$ 5 deg/sec) does not permit proper input design; the values of these derivatives that were used, based on the ground simulator and initial attempts at data identification, are summarized in Table 5-5 for the three duct angles of interest:

Table 5-5

APPROXIMATE DUCT ANGLE EFFECTIVENESS DERIVATIVES

	X_λ	Z_λ	M_λ
100 Kt	-.285	-1.294	.006
65 Kt	-.690	- .450	.015
0 Kt	-.460	0.0	0.0

The characteristics of the DVC system that are documented in this report use the actual aircraft aerodynamic characteristics as determined by identification from flight data (Appendix IV) for all the derivatives except the duct angle effectiveness, for which the approximate values listed in Table 5-5 were used.

The calculation of the feedback gains was performed using linear optimal control theory, and utilized the model-in-the-performance-index technique to approach the desired decoupling characteristics. Hence:

$$PI = \frac{1}{2}\int_0^\infty \left\{\left[\dot{\hat{y}} - \hat{F}_D \hat{y}\right]^T Q \left[\dot{\hat{y}} - F_D \hat{y}\right] + u_2^T R u_2\right\} dt \qquad (5\text{-}5)$$

Subject to:

$$\dot{\hat{y}} = \hat{F}\hat{y} + \hat{G}_2 u_2$$

$$u_2 = -K_2 \hat{y}$$

$$\dot{\hat{y}}_D = \hat{F}_D \hat{y}_D$$

Where:

$$u_2 = (\Delta_{es}, \Delta_{cs})^T, \quad K = \begin{bmatrix} K_2 \\ \hline 0 \end{bmatrix}, \quad \hat{G} = \left[\begin{array}{c|c} & 0 \\ & 0 \\ \hat{G}_2 & 0 \\ & 0 \\ & 1 \end{array}\right]$$

The solution to Equation 5-5 was obtained for the five duct angle cases using:

$$\begin{aligned} Q &= \text{diag}\left[10,\ 10,\ 1,\ 1,\ 1\right] \\ R &= \text{diag}\left[30,\ 10\right] \end{aligned} \tag{5-6}$$

This design procedure resulted in five sets of feedback gains, one for each duct angle. Implementation of these gains as scheduled functions of duct angle was considered undesirable, however, because of the system complexity involved. Examination of the time history responses at 100 Kt and 0 Kt using gains fixed at the 65 Kt values indicated acceptable results, although some degradation in decoupling at 0 Kts is evident (see Appendix II). On this basis, these gain values were implemented as constants independent of duct angle; the values used are given along with a schematic diagram of the DVC implementation in Figure 5-5.

The calculation of the control cross-feeds was performed using a weighted static error minimization procedure; other techniques (least square and equation error minimization) were investigated but the results were unsatisfactory (Reference 34). This procedure seeks the minimum of a weighted least square error of the steady-state responses as follows.

Considering only the controllers $\left[\delta_{es}, \delta_{cs}\right]$, the closed-loop equations of motion are:

$$\dot{\hat{y}} = (\hat{F} - \hat{G}K)\,\hat{y} + \hat{G}_2 J_2 \omega_2 \tag{5-7}$$

where $\omega_2 = \left[\delta_{es}\ ,\ \delta_{cs}\right]$

Assuming a stable system (guaranteed by the use of linear optimal control), the steady state is:

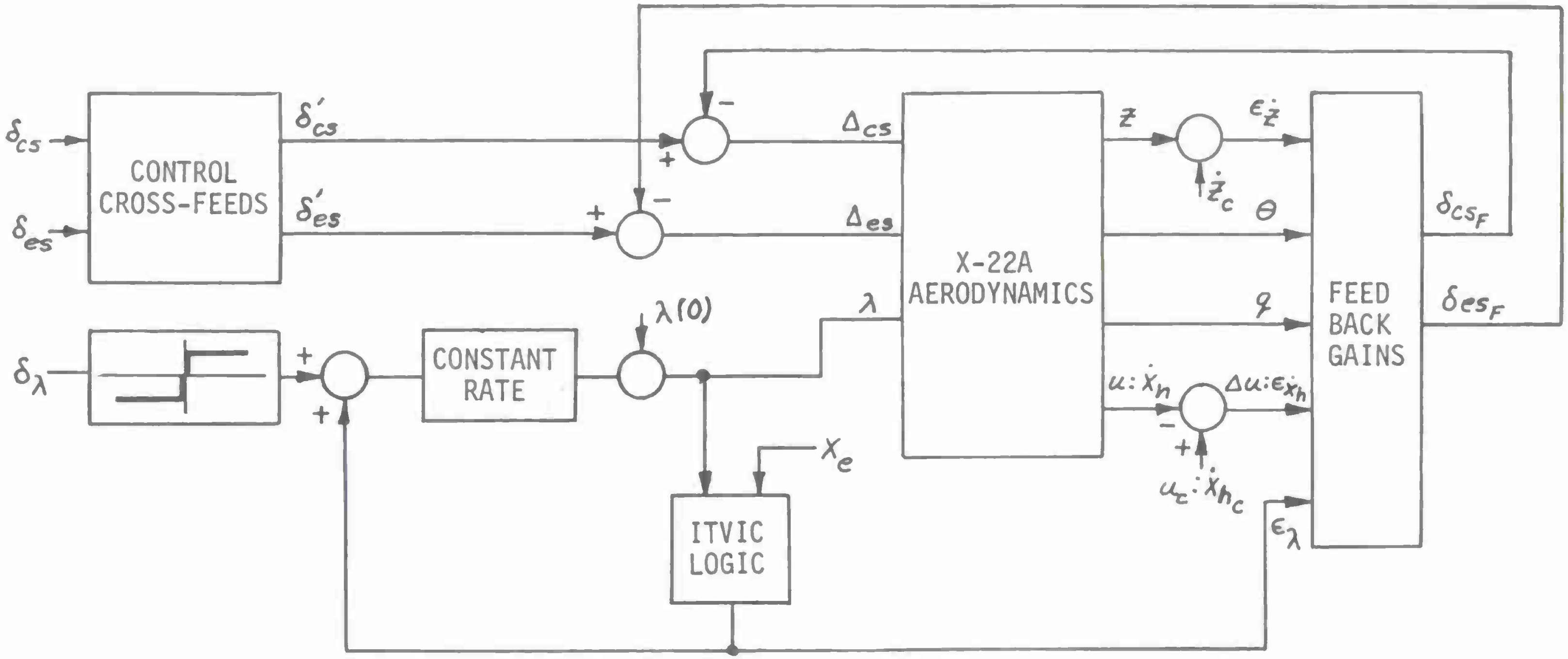
$$\begin{aligned} \hat{y} &= -(\hat{F} - \hat{G}K)^{-1} G_2 J_2 \omega_2 \\ &\triangleq -P J_2 \omega_2 \end{aligned} \tag{5-8}$$

The object is to minimize $\epsilon = \left\| \hat{y} - y_D \right\|_Q^2$ the solution to which is:

$$J_2 = -(P^T Q P)^{-1} P^T Q \hat{y}_D \tag{5-9}$$

Since $(\hat{F} - \hat{G}K)$ does not exist in this application, Equation 5-9 was solved by partitioning and reducing Q to the appropriate dimension; the value of Q used was

$$Q = diag\left[10, 10, 1, 0\right] \tag{5-10}$$



CROSS-FEED GAINS:

Δ_{es}/δ_{es} = 5.73 $\qquad$ Δ_{cs}/δ_{es} = 0

Δ_{es}/δ_{cs} = 3.84 (λ = 0) $\qquad$ Δ_{cs}/δ_{cs} = 2.26

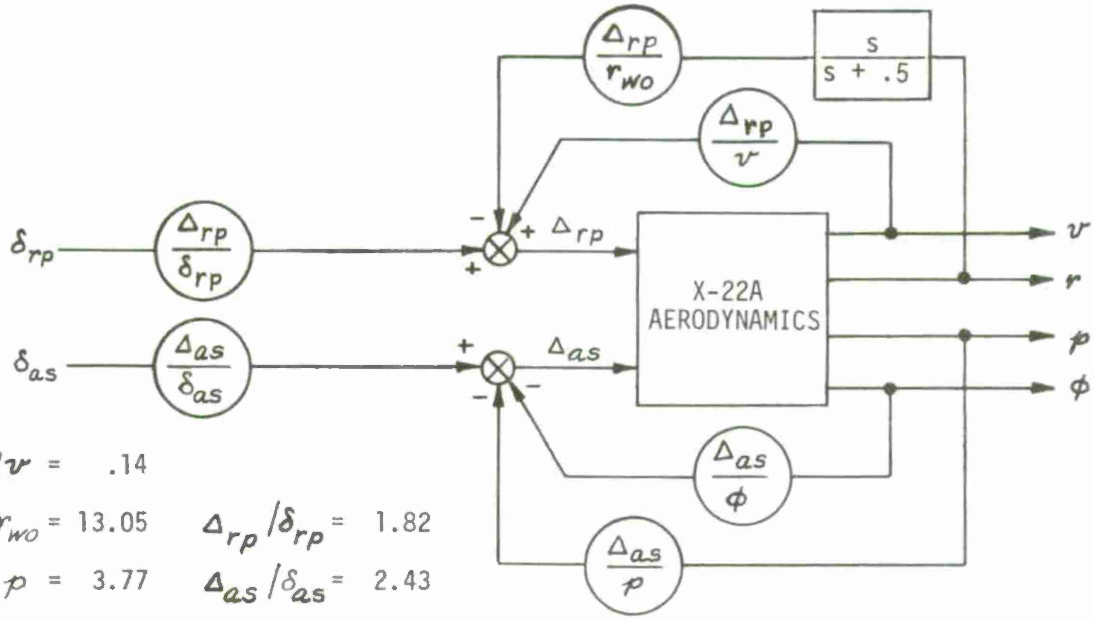
$\downarrow$

0.0 (λ = 90)

FEEDBACK GAINS:

$\Delta_{es}/\epsilon_{\dot{x}}$ =	.195	$\Delta_{cs}/\epsilon_{\dot{x}}$ =	-.07
$\Delta_{es}/\epsilon_{\dot{z}}$ =	-.19	$\Delta_{cs}/\epsilon_{\dot{z}}$ =	-.52
Δ_{es}/θ =	38.4	Δ_{cs}/θ =	13.5
Δ_{es}/q =	18.9	Δ_{cs}/q =	2.12
$\Delta_{es}/\epsilon_\lambda$ =	-.2	$\Delta_{cs}/\epsilon_\lambda$ =	.145

Figure 5-5a IMPLEMENTATION OF DECOUPLED VELOCITY CONTROL SYSTEM (LONGITUDINAL)



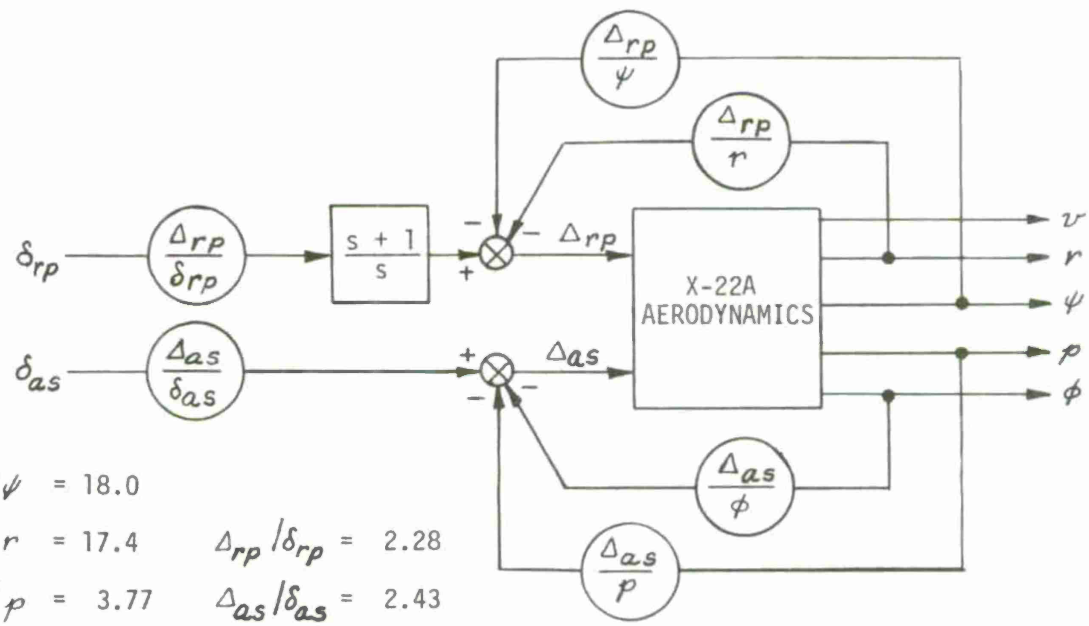
Δ_{rp}/v = .14

Δ_{rp}/r_{wo} = 13.05 Δ_{rp}/δ_{rp} = 1.82

Δ_{as}/p = 3.77 Δ_{as}/δ_{as} = 2.43

Δ_{as}/ϕ = 13.20

Turn-following (ATC)



Δ_{rp}/ψ = 18.0

Δ_{rp}/r = 17.4 Δ_{rp}/δ_{rp} = 2.28

Δ_{as}/p = 3.77 Δ_{as}/δ_{as} = 2.43

Δ_{as}/ϕ = 13.20

Heading-hold (HH)

Figure 5-5b IMPLEMENTATION OF DECOUPLED VELOCITY CONTROL SYSTEM (LATERAL-DIRECTIONAL)

The control gain matrix was again calculated at five duct angles. The "through feed" gains (Δ_{es}/δ_{es}, Δ_c/δ_{cs}) did not vary substantially, and were therefore held constant at nominal values. The "cross-feed" gain of collective-to-longitudinal-stick (Δ_{cs}/δ_{es}) was set to zero after the ground simulator check showed significant coupling of vertical velocity to longitudinal stick near the hover. The remaining "cross-feed" gain (Δ_{es}/δ_{cs}) was approximated as a linear function of duct angle: the primary purpose of this gain is to minimize the pilot's pitch input during glide slope acquisition. The control gains used are listed in Figure 5-5; the resulting DVC transfer functions and frequency responses are given in Appendices I and II. As an indication of the primary response characteristics of this control system, the longitudinal velocity ($\dot{X}_e$) to duct angle inputs (δ_λ) and the vertical velocity ($\dot{h}$) to collective stick inputs (δ_{cs}) are summarized below in Table 5-6:

Table 5-6

DVC LONGITUDINAL AND VERTICAL VELOCITY TRANSFER FUNCTIONS

	$\dot{X}_e/\delta_\lambda$	$\dot{h}/\delta_{cs}$
100 Kt	$\frac{2.09(4.02)[.79;3.58]}{(0)(2.04)(.83)[.88;2.47]}$	$\frac{-3.49(0)(-6.3)(.72)(.21)}{(0)(2.04)(.83)[.88;2.47]}$
65 Kt	$\frac{4.18(1.33)[.7;4.06]}{(0)(1.45)(.43)[.86;3.42]}$	$\frac{2.26(0)(.35)[.57;5.07]}{(0)(1.45)(.43)[.86;3.42]}$
0 Kt	$\frac{2.44(.89)[.73;4.11]}{(0)[.96;.58][.90;3.54]}$	$\frac{3.39(0)(.39)[.89;3.45]}{(0)[.96;.58][.90;3.54]}$

To summarize, the following points concerning the design and implementation of the decoupled velocity control system are noted:

- The control augmentation design was based on preliminary estimates of the basic X-22A stability and control derivatives, and this fact coupled with the more severe restriction of selecting all but one feedback and control gain to be constant results in dynamic characteristics that vary somewhat with duct angle and responses to control inputs that are imperfectly decoupled. The implementation of the system might be considered "open-loop" model following in that measured differences between the actual and desired responses are not available as additional feedbacks to help improve system performance; in common with all response feedback implementations, therefore, imperfections in the knowledge of the controlled velicle introduce variations in the resulting dynamic characteristics. Nonetheless, as can be seen from the frequency responses given in Appendix II, this system did provide augmented longitudinal and lateral velocity responses and a substantial degree of decoupling.

- The system was designed and implemented as a three-controller situation longitudinally: duct angle (δ_λ), collective stick (δ_{cs}), and longitudinal stick (δ_{es}). During preliminary flight checkouts, attempts were made to blend the duct angle control into the pitch controller: the pitch stick commanded attitude only for small inputs (approximately + 1 degree, -2 degrees) and duct rotation plus attitude for larger inputs (rotation toward 90° for nose-up inputs). This blending proved unacceptable primarily because relatively large nose-down stick inputs are required for trim (even with attitude augmentation) as speed decreases to around 30 Kt in the X-22A. Although implementations using trim stick position as a function of duct angle for the null position, or using actual pitch attitude instead of commanded attitude were possible solutions to the problem, it was decided not to pursue this approach. Since automatic duct rotation is used with the system, control of longitudinal velocity with the duct angle is not a primary control until the hover anyway, and the use of a separate controller (duct rotation rate ON-OFF button) for velocity in the hover was not considered objectionable by the pilot.

- No attempt was made to provide a direct lateral velocity control. The lateral and directional augmentation implementations were identical to the attitude command control system.

5.7 COMPARISON WITH MIL-F-83300 REQUIREMENTS

As was discussed at the beginning of this section, the design of the control systems that were investigated in this experiment was based on attempting to achieve "good" characteristics for each type so that differences in the pilot ratings obtained would be based primarily on the generic level of complexity and would not be unduly influenced by poor flying qualities of a given type. Toward this end, the flying qualities requirements given in MIL-F-83300 (Reference 4) were used as a guide where possible; the main emphasis was on the requirements for aircraft characteristic modes, control sensitivities, and control forces, brief discussions of which are given in the following paragraphs. Unless otherwise noted, the discussions are based on the requirements for Level 1 flying qualities, which in this case have been interpreted as providing a Cooper-Harper pilot rating of better than 3-1/2 (see Reference 4 for a discussion of the concept of Levels). Sufficient information is presented in Appendix I of this report for the interested reader to perform additional comparisons if desired.

5.7.1 Longitudinal Dynamics: Hover (3.2.2.1)*

The requirement for the longitudinal characteristic roots in hover states that all aperiodic roots shall be stable, and places boundaries on allowable oscillatory roots which are reproduced here as Figure 5-6. The longitudinal characteristic roots at hover of the rate augmentation, attitude command (excluding prefilter roots at s = -1.4 ± j 1.42), and direct velocity control system are repeated in Table 5-7:

Table 5-7

LONGITUDINAL HOVER CHARACTERISTIC ROOTS

RATE	s = -.12, s = -2.94, s = -.042 ± j .40
ATTITUDE	s = -.12, s = -.17, s =-.3.16 ± j 2.90
DVC	s = -3.17 ± j 1.57, s = -.55 ± j .16 (Additional s=0 due to λ controller)

No unstable aperiodic roots exist for any system; the oscillatory roots are shown on Figure 5-6 and can be seen to meet the requirements. Hence all the control systems meet the Level 1 longitudinal hover requirement of 3.2.2.1.

5.7.2 Lateral Dynamics: Hover (3.2.2.1, 3.2.2.2)

The primary requirement for the lateral characteristic roots in hover (3.2.2.1) is the same as for the longitudinal roots. Table 5-8 repeats the rate augmentation, attitude/rate (excluding prefilter root at s = 0) and attitude command characteristic roots at hover, assuming the heading-hold (HH) mode is used for the latter two.

Table 5-8

LATERAL HOVER CHARACTERISTIC ROOTS

RATE	s = -1.62, s = -2.71, s = +.012 ± j .45
ATT/RATE	s = -.17, s -1.67, s = -2.60, s = -1.11± j 1.83
ATTITUDE	s = -.16, s = -1.70,s = -2.48, s = -.66 ± j 2.10

*The numbers in parentheses are the applicable requirement from Reference 4.

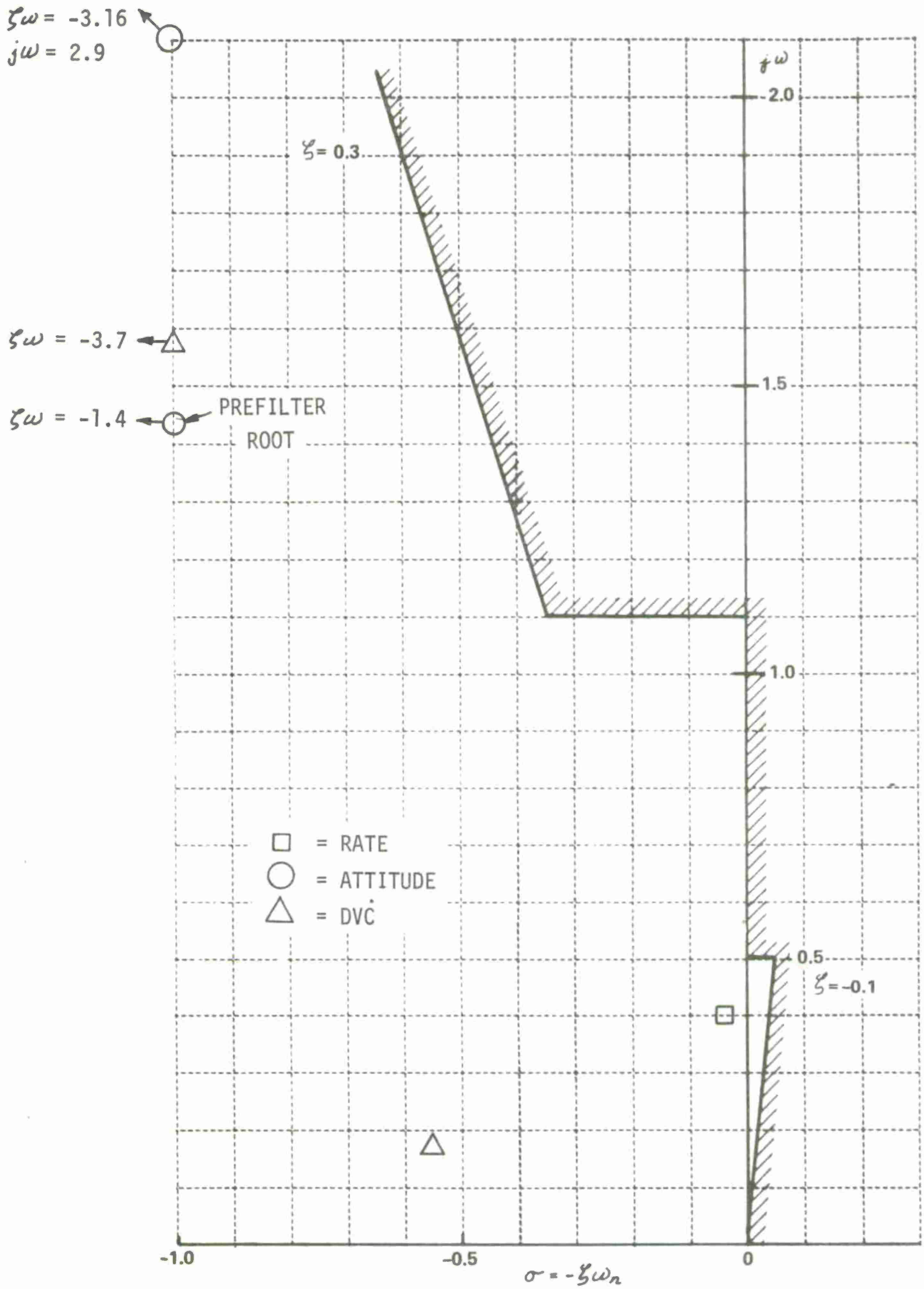


Figure 5-6 LEVEL 1 AND LEVEL 2 IFR s-PLANE OSCILLATORY MODE BOUNDARY FROM REFERENCE 4

Again, the aperiodic roots are stable, and as is shown in Figure 5-7, all oscillatory roots are within the boundaries. Hence all the control systems meet the Level 1 lateral hover requirements also.

An additional requirement on the lateral characteristics is given by 3.2.2.2, which states that the yaw mode time constant shall not exceed 1.0 second for Level 1. For the rate augmentation system, this time constant is $\tau = 1/1.62 = .62$, which meets the specification. For the attitude/rate and attitude command systems with the heading-hold directional mode engaged, the r/δ_{RP} transfer function is approximately:

$$r/\delta_{RP} \cong \frac{.52(s+1)}{(s+1.7)(s+2.48)}$$

This response meets the intent of the specification; although no time constant is directly obtainable, the rise time corresponds to a first order system with $\tau \cong 0.4$ to 0.5.

5.7.3 Vertical Response: Hover (3.2.5.3 and 3.2.5.4)

Requirement 3.2.5.3 states that the vertical velocity response in hover to a one inch thrust input shall be more than 100 ft/minute and less than 750 ft/minute; Requirement 3.2.5.4 states that the vertical damping shall be stable. The vertical damping roots for the rate augmentation and attitude command systems are $s = -.12$ in Table 5-7, and $s = -.55 \pm j\,0.16$ for the decoupled velocity control system; all are stable and satisfy 3.2.5.4. The responses at one second may be approximated by (see the transfer functions in Appendix I), for a one degree control input:

RATE: $\dot{h}(1) \cong \frac{1.875}{.12}\left(1 - e^{-.12}\right) = 110 \text{ fpm}$

ATTITUDE: $\dot{h}(1) \cong \frac{1.875}{.12}\left(1 - e^{-.12}\right) = 110 \text{ fpm}$

DVC: $\dot{h}(1) \cong 3.39\left[\frac{.39}{(.58)^2} + \frac{1}{.58}\left(.19 - \frac{.39}{.58}\right)e^{-.58}\right] = 200 \text{ fpm}$

Both of these vertical response requirements were therefore met by all the control systems, whether or not vertical damping was augmented, in terms of degrees of collective.

5.7.4 Attitude Response: Hover (3.2.3.2)

As with the vertical response requirement, MIL-F-83300 does not specify moment control sensitivities directly, but instead places requirements on attitude response at one second to a one inch control input; these requirements are, for Level 1:

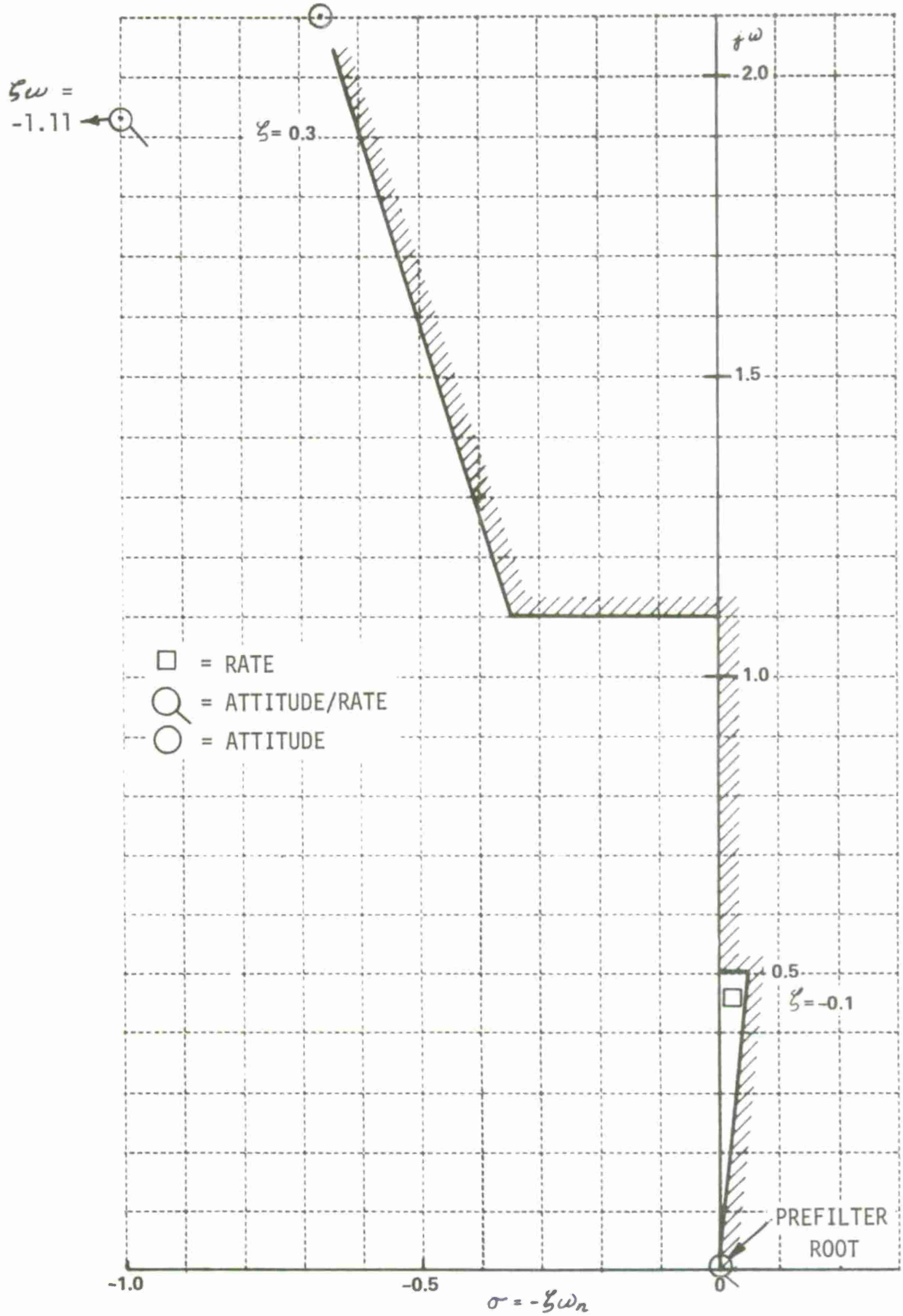


Figure 5-7 LEVEL 1 AND LEVEL 2 IFR s-PLANE OSCILLATORY MODE BOUNDARY FROM REFERENCE 4

$$3 \text{ deg} < \theta(1) < 20 \text{ deg}$$

$$4 \text{ deg} < \phi(1) < 20 \text{ deg}$$

$$6 \text{ deg} < \psi(1) < 20 \text{ deg}$$

The time histories shown in Appendix II may be used to demonstrate compliance. The attitudes at 1 second are summarized in Table 5-9, assuming the heading hold mode engaged for the applicable systems.

Table 5-9

ATTITUDE RESPONSES (DEGREES) AT 1 SECOND TO 1 INCH INPUT

	$\theta(1)$	$\phi(1)$	$\psi(1)$
RATE	5.7	5.7	4.7
ATT/RT	4.0	7.7	12.4
ATTITUDE	4.0	11.7	12.4
DVC	7.8	11.7	12.4

As can be seen, with the exception of the RATE yaw response, the Level 1 criteria are met. The yaw attitude response for the RATE system is somewhat low because the basic X-22A control gearing was used as a representative value.

5.7.5 Control Forces: Hover (3.5.1.1, 3.5.1.2)

These two requirements place ranges on allowable breakout forces and gradients in the control system, and are summarized for Level 1 as:

Table 5-10

MIL-F-83300 BREAKOUT AND GRADIENT REQUIREMENTS

	Pitch	Roll	Yaw
Breakout (lbs)	.5 to 1.5	.5 to 1.5	2.0 to 7.0
Gradients (lb/inch)	.5 to 3.0	.5 to 2.5	5.0 to 10.0

The breakouts and gradients implemented on the variable feel system of the X-22A are summarized in Table 5-11; these values were constant for all speeds between 100 Kt and hover, and were the same for all control systems with the exception of the pitch stick gradient, which was doubled for the decoupled velocity control system.

Table 5-11

CONTROL FORCES USED IN EXPERIMENT

	Pitch	Roll	Yaw
Breakout (lbs)	.5	.5	9.1
Gradients (lb/inch)	3.45(6.9)	1.9	25.0

It may be seen that the pitch gradient is somewhat higher than the criterion value: this compromise was based on having a reasonable gradient for forward flight without gain scheduling. Similarly, the extremely high (for hover) rudder forces were chosen based on the value used in a previous X-22A experiment (Reference 11), and are based on forward flight considerations. It is noted here that the force-feel dynamics were $\zeta = 0.7$, $\omega_n = 12$ rad/sec, and were considered sufficiently "fast" to not degrade the flying qualities evaluations.

5.7.6 Longitudinal Dynamics: 100 Kt (3.3.2)

The requirement on the longitudinal characteristic roots in forward flight states that all roots shall be stable and, further, that the pair which primarily determine the "short term" response will fall within the boundaries reproduced in Figure 5-8. The longitudinal characteristic roots are summarized in Table 5-12, excluding the prefilter roots at $s = -1.4 \pm j\,1.42$:

Table 5-12

LONGITUDINAL CHARACTERISTIC ROOTS AT 100 KT

RATE	$s = -.93$, $s = -2.89$, $s = -.31$, $s = +.12$
ATT/RT AH	$s = -.23$, $s = -.55$, $s = -3.1 \pm j\,2.67$
DVC	$s = -2.04$, $s = -.83$, $s = -2.17 \pm j\,1.17$ (Additional $s = 0$ due to λ controller)

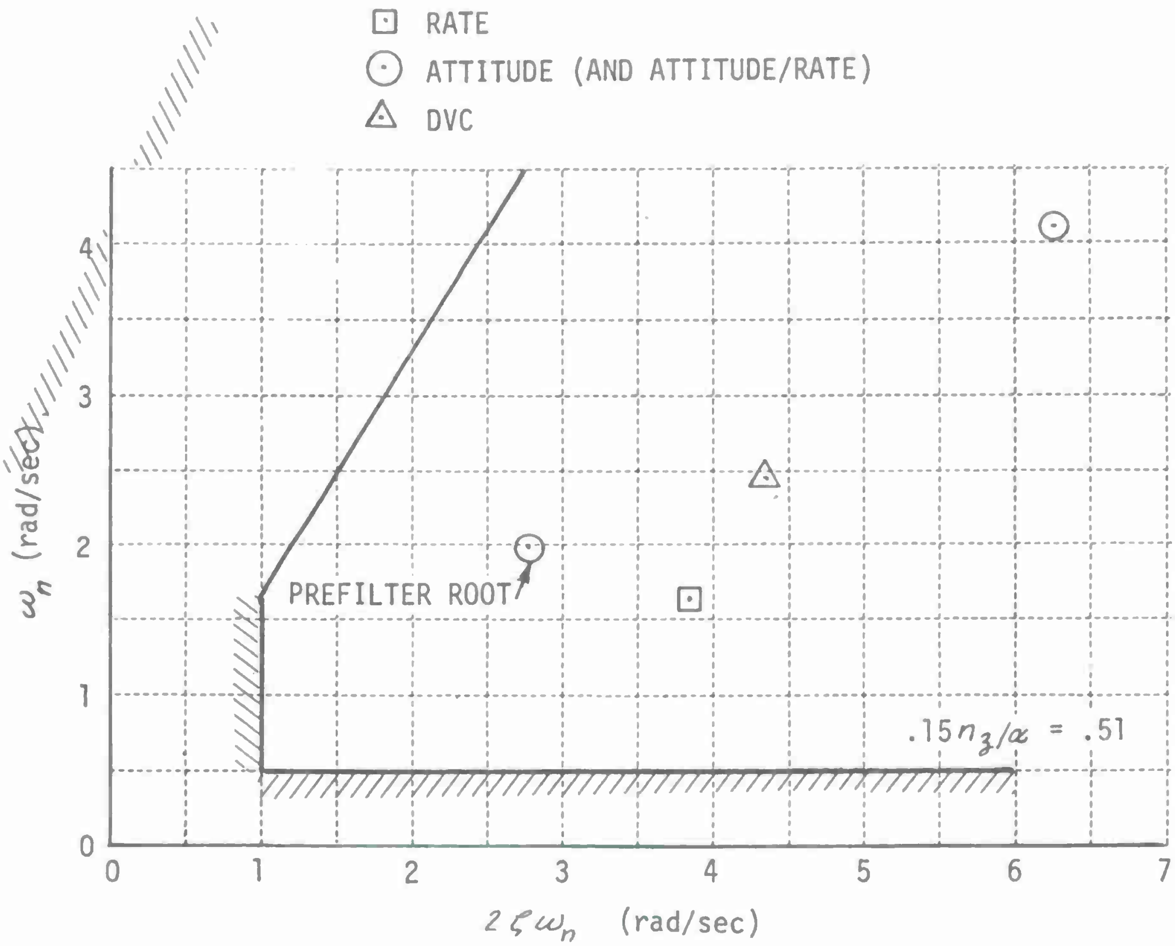


Figure 5-8 SHORT-TERM RESPONSE REQUIREMENT FROM REFERENCE 4

As can be seen, the rate augmentation system has one unstable root, which is caused by the unstable value of M_u ; no attempt was made to alter this root, because a previous STOL X-22A experiment indicated satisfactory ratings were obtainable with a similar divergent root (see Configuration 14 of Reference 10). No unstable roots exist for the other control systems. The short-term requirements are met by all the control systems (Figure 5-8).

5.7.7 Lateral-Directional Dynamics: 100 KT (3.3.7.1, 3.3.7.2, 3.3.7.3)

The requirements on the lateral-directional characteristic roots are given in terms of allowable spiral instability, roll mode time constant, and Dutch roll frequency and damping, and are:

Spiral: Time to double amplitude greater than 20 seconds

Roll Mode: Time constant less than 1.4 seconds

Dutch Roll: Within the boundaries reproduced in Figure 5-9.

The characteristic roots of the rate augmentation, attitude/rate (excluding prefilter), and attitude command (also used with DVC) systems are summarized in Table 5-13, assuming the turn-following mode (ATC) is selected for the latter two:

Table 5-13

LATERAL DIRECTIONAL CHARACTERISTICS AT 100 KT

RATE	s = -.14, s = -3.14, s = -.57 ± j 1.22
ATT/RT	s = -1.11 ± j 2.27, s = -1.23 ± j .84 (Plus root at s = -.52 due to washout)
ATTITUDE	s = -.79 ± j 2.54, s = -1.05 ± j .94 (Plus root at s = -.52 due to washout)

For the rate augmentation system, the spiral is stable and meets the requirement, and the roll mode time constant is 0.32 seconds, which meets the requirement. For the attitude/rate system, the prefilter introduces a root at the origin, and the zero provides a rate command with time constant equivalent to approximately 0.5 seconds, and hence this system meets the requirement. The requirement is not written in a form compatible with an attitude command system, but the second-order characteristics of this system are the same as a satisfactory longitudinal system. The Dutch roll roots are shown in Figure 5-9 and all meet the requirement. Hence, all the lateral-directional characteristics modes satisfy the MIL-F-83300 requirements.

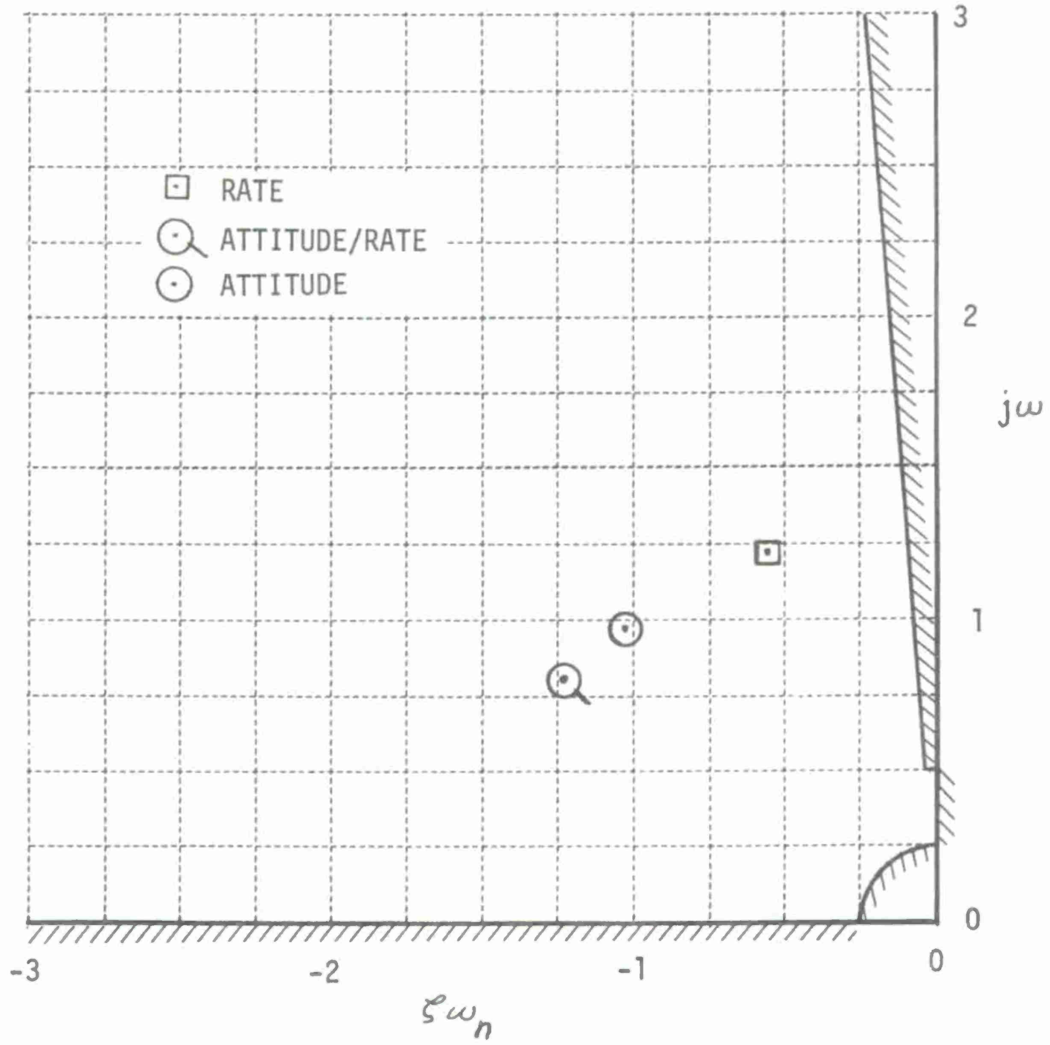


Figure 5-9 DUTCH ROLL REQUIREMENT FROM REFERENCE 4

5.8 SUMMARY

This section has reviewed the dynamic characteristics of the control systems investigated in this experiment and shown their general compliance with the requirements of MIL-F-83300. A qualitative list of the increasing complexity is given in Table 5-14.

Table 5-14

QUALITATIVE SUMMARY OF CONTROL SYSTEM COMPLEXITY

	Angular Aug.	Automation	Translational Aug.
RATE	Min.	None	None
ATT/RATE	Max.	↓	↓
ATTITUDE	↓	↓	↓
AUTO	↓	λ	↓
DVC	↓	↓	$\dot{X}_e$, $\dot{h}$, Decoupling

Section VI

DISPLAY DESIGN

6.1 SYNOPSIS OF SECTION

One of the two major variables of this experiment was information display sophistication, the development of which will be discussed in this section. In the context of this experiment, display "sophistication" comprises a hierarchy of information levels displayed to the pilot in an ergonomically acceptable fashion; hence the first portion of the section is devoted to the general information requirements, independent of display technique, of a human pilot conducting a decelerating, descending V/STOL instrument landing approach. Next the generic levels of displayed information chosen for the experiment and a rationale for their selection are described. The design of the experimental display formats and their modification as a result of preliminary ground simulation and flight testing are then discussed; included in this discussion is a detailed description of each display format. Finally, the synthesis of the control director logic for the director display formats is described.

6.2 INFORMATION REQUIREMENTS

The cockpit displays of V/STOL aircraft must convey a larger quantity of information to the pilot for the instrument landing approach than their counterparts in CTOL aircraft for the corresponding task. The factors involved in this requirement include:

- the increased dimensions of the task itself - including continuous control of the aircraft velocity vector during a decelerating descent,
- the presence of at least one additional controller to effect the conversion from aerodynamic lift to powered lift, and
- the need for sufficient information to control, or to monitor the automatic control of, each of the six degrees of freedom of the aircraft.

Various independent efforts have been made to establish the information requirements of the pilot of a VTOL aircraft during an instrument approach to the hover: for example, a NASA study (Reference 36), a JANAIR-sponsored program (Reference 37), and the report of the AGARD Working Group cited previously (Reference 13). The AGARD report considered an instrument approach and visual landing task while the remaining two assumed the landing phase to be carried out on instruments as well. Furthermore, the AGARD report assumed a highly augmented aircraft while the NASA and JANAIR studies made no apparent assumptions concerning controlled vehicle characteristics. Table 6-1 is a summary of the information requirements from those references, re-ordered for the sake of clarity; information required for system management duties (e.g., radio tuning, engine monitoring) is deleted:

Table 6-1

INFORMATION REQUIREMENTS FOR V/STOL INSTRUMENT LANDINGS

Information Level	Requirement
Orientation	Pitch, Roll, and Heading Desired Approach Course
Position Status	Height - Radar Altitude (Baro. Alt. for Initial Approach) Range-To-Go Relative Bearing of Touchdown Point
Velocity Status	Airspeed and Groundspeed AGARD: Airspeed for aerodynamic lift regime, groundspeed for powered lift regime, smooth transition between A/S and G/S JANAIR and NASA: Both required Instantaneous Vertical Velocity
Position Error	Vertical and Lateral Flight Path Error (Approach) Longitudinal and Lateral Position Error (Hover - JANAIR)
Velocity Error (AGARD)	A/S-G/S Deviations Vertical Speed Deviation
Miscellaneous (AGARD)	Thrust Vector Angle Angle of Attack and Limits - Aerodynamic Lift Only Sideslip or Lateral Acceleration and Limits Wind Vector

Because of the plethora of information required by the pilot for the stabilization and control of even a highly-augmented VTOL aircraft during a landing approach, conventional electromechanical instruments, due to their limited versatility, have been judged unsuitable because of the excessively high mental workload required for the gathering of information and the subsequent decision-making process (Reference 13). The need for combined (co-located but separate parameters) or integrated (one display element for several parameters) electronic displays was suggested in Reference 13 and established for the helicopter by NASA Langley Research Center's VTOL Approach and Landing Technology (VALT) Program (Reference 5) and for the vectored-thrust VTOL aircraft by the results of the initial X-22A ground simulator study (Reference 12). The cathode ray tube (CRT) is the best existing display device for the high data density required in integrated displays and hence was selected as the basis for the X-22A's electronic display system, described in detail in Reference 25 and Appendix VIII.

6.3 DISPLAYED INFORMATION AS AN EXPERIMENTAL VARIABLE

It is evident from a survey of current V/STOL electronic displays that the display designer, as a rule, tends to emphasize the display medium to the detriment of the message. The AGARD Working Group concluded that: "It is more important to get the intrinsic information correct than to follow slavishly any given presentation" (Reference 13). Accordingly, the major display variable for this experiment was the level of information displayed to the evaluation pilot on his CRT instrument. A hierarchy of three generic levels of displayed information was selected and designated as follows:

- ED-1: orientation, position, and commanded position
- ED-2: orientation, position, commanded position, velocity and commanded velocity information
- ED-3: orientation, position, commanded position and velocity, with longitudinal (δ_{es}), lateral (δ_{as}), and collective (δ_{cs}) control director information.

From a practical point of view, the hypothesized reduction in pilot workload caused by increasing levels of displayed information must be balanced against the increasing cost of deriving that information from more sophisticated sensors through more complex data processing. This experiment was designed in part to provide a valid basis for the pilot-oriented portion of that tradeoff.

The least sophisticated electronic display format, ED-1, presented the pilot raw aircraft position in three dimensions. This level of information requires a relatively simple guidance system: an ILS with precision DME or ILS and on-board radar altimeter for example; in addition, a minimum of on-board data processing is required, primarily to convert the angular position information to a rectangular coordinate system for display to the pilot. Although probably

unacceptable for less complex control systems, it was hypothesized that this format may be sufficient if the pilot is provided with augmented control of the aircraft velocity vector.

The ED-2 format is of the type espoused by Dukes for attitude-stabilized helicopters in a precision hover task (Reference 14). A more sophisticated guidance system and/or a more complex airborne sensor package are required to provide valid ground velocity data for display in all phases of the approach: that is, either an inertial navigation system or complementary filtering of radar and on-board aircraft data must be provided.

The ED-3 format represents an attempt to achieve the integration of command and status information recommended as a result of NASA's VALT program to date (Reference 5). Control director displays ideally serve to cause pilot/aircraft system performance to approach that of a well-designed automatic control system; furthermore directors may be a requirement in the case of marginally stable or unstable controlled vehicles in order to decrease the pilot's mental workload to acceptable levels by reducing his control and stabilization functions to a task of nulling individual director elements. However, as Reference 13 concludes: "Even though the utilization of director displays can improve the performance of a pilot in specific control tasks, his confidence can be undermined if adequate situation information is not provided as well." Director displays require more complex on-board data processing in order to derive the signals to drive the individual director elements; V/STOL aircraft may require even more complex control director logic than CTOL aircraft because of the drastic changes that occur in basic aircraft flying qualities during the conversion from the aerodynamic lift to the powered lift flight regimes.

The information levels on which the display formats are based were assumed essentially consistent in all three axes for the electronic display design. Specifically, it was not considered useful to consider velocity information to be available in one plane (e.g., vertical) and not the others; as will be discussed, however, the pilot workload in the vertical plane was sufficiently high to warrant the inclusion of one "mixed" format which included a collective stick control director but no longitudinal or lateral directors. This philosophy of consistent information levels provides a rational basis for the investigation of the hierarchical display requirements as a function of control system complexity that was the primary objective of this program.

In addition to the central electronic display, the evaluation pilot was provided with several peripheral instruments for additional required information. A schematic diagram of the evaluation pilot's instrument panel is given in Figure 6-1. With the exception of the configuration change director light and three-axis electromechanical control director elements, this auxiliary information remained constant throughout the experiment. Table 6-2 summarizes the fixed information and the instruments supplying that information in a form suitable for comparison with Table 6-1; the information provided by electronic display format ED-1 constitutes the fixed information displayed by the CRT.

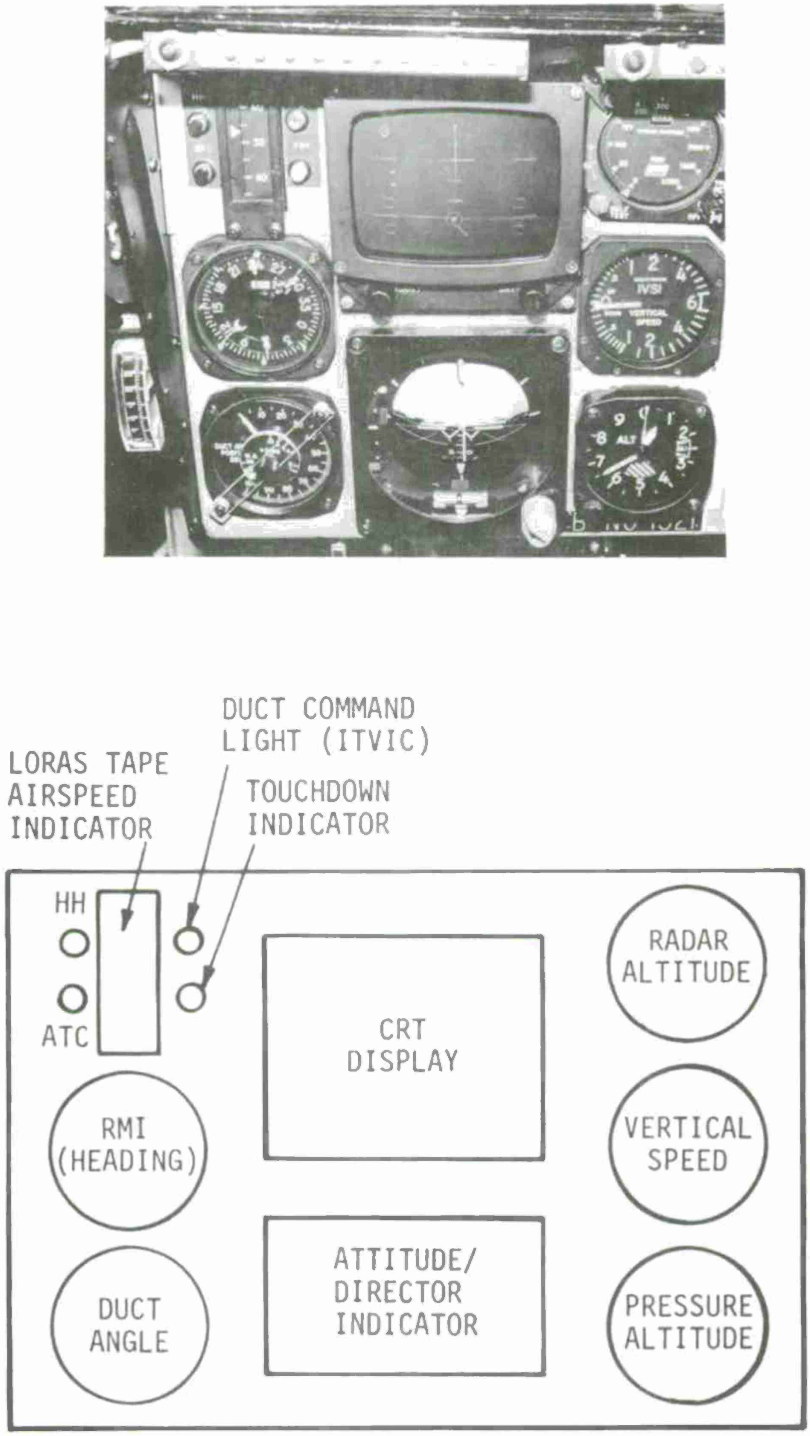


Figure 6-1 EVALUATION PILOT INSTRUMENT PANEL

Table 6-2

FIXED INFORMATION DISPLAY

Information Category	Information	Instrument
Orientation	Pitch, Roll	Attitude Indicator, ED
	Heading	RMI, ED
	Approach Course	ED
Position Status	Height	Radar Altimeter Barometric Altimeter
	Range and Relative Bearing of Touchdown Point	ED
Velocity Status	Longitudinal Airspeed	LORAS Tape Instrument
	Vertical Speed	IVSI
Position Error	Altitude Error Lateral Position Error	ED
Miscellaneous	Thrust Vector Angle	Duct Angle Instrument
	Yaw Rate Lateral Acceleration	Needle/Ball

According to the display principles to be presented in the following subsection, the altimeters and vertical speed instrument should ideally have been located on the left-hand side of the instrument panel and the airspeed indicator on the right for a more natural association with the primary vertical motion controller, the collective stick (on the evaluation pilot's left), and the primary horizontal motion controller, the center stick, respectively. Instrument panel geometry limitations precluded this arrangement however; hence the final instrument display configuration was as depicted in Figure 6-1.

6.4 DESIGN AND DEVELOPMENT OF THE ELECTRONIC DISPLAY FORMATS

Following the selection of the various information levels to be investigated in the experiment, the design of the electronic display formats to convey this information to the pilot was begun. As suggested by Reference 13, a single combined vertical and horizontal display format was selected as the basis for all the electronic display configurations investigated in the experiment. It was the intent from the outset to present the displayed information to the pilot in as favorable a manner as possible so that any display-related deficiencies would be a result of lack of information and not of display design problems. Therefore, many of the integrated display principles of Dukes (Reference 38) and Young (Reference 39) were applied to the design of the three basic electronic display formats. In particular, the following guidelines were adopted:

- Aircraft-referenced display - The aircraft symbol position is fixed and the other displayed information moves with respect to this reference.

- Error display - The guidance information is presented in the form of errors rather than as absolute values where possible.

- Explicit display of rates - No attempt is made to have the pilot estimate absolute or error rates implicitly by the rate of change of a position symbol on the display. When rates are displayed, they are displayed explicitly.

- Display of lead information - When rate information is displayed, its function is to lead the position symbol to aid the pilot in his prediction of a future aircraft state.

- Symbol response to control input - The location of a symbol and the sense of its motion are selected to be compatible with the location and motion of its primary controller.

- Scaling of the displayed parameters - The scaling of the various symbol motions is selected so as to be acceptable to the pilot while not significantly degrading overall system performance. A relatively simple display with fast-moving symbols may appear "cluttered" to the pilot while a more complex display with slow-moving symbols may be acceptable to him but may also result in a relatively poor total system performance.

The choice of symbology, although not as significant as the previous considerations, is important insofar as it relates to the ability of the pilot

to decode the information as it is presented to him. He must never be in doubt about the status of his aircraft because of momentary confusion about the meaning of a particular symbol. An extensive literature survey, opinions of Calspan's pilot/engineers, and the results of preliminary ground- and in-flight simulatiion were all used to decide upon the final version of the electronic display symbology (Figure 6-2). The techniques used to display the required information were drawn primarily from two sources and modified as required; for example, the aircraft symbol, horizontal velocity vector, and vertical velocity/position display are based upon Dukes' helicopter display work (Reference 14), while the expanding landing pad symbol was used as part of the RAE display format evaluated in the CL-84 Tripartite Program (References 16 and 17). Ground simulation (Appendix III) and preliminary flight testing resulted in the following format alterations.

Ground Simulation:

- the implementation of an artificial horizon which extended the full width of the display (rather than the "peripheral" display of attitude used by Dukes in Reference 14) to provide a more compelling display of aircraft orientation.

- a continuous increase in the sensitivity of the horizontal position scaling with decreasing range rather than the discrete scale change used in Reference 12.

Flight Testing:

- a change in the sense of the altitude error diamond to "fly to".

- a shift to an aircraft heading-referenced display of position and velocity at or near the hover.

- a discrete increase in sensitivity of the velocity vector and command diamond symbols at or near the hover.

- a new display format, ED-2+ (Figure 6-2), which substituted a collective control director for the altitude rate deviation symbol of format ED-2 in an attempt to alleviate the high pilot workload required in the control of vertical flight path errors.

As explained previously in Section 6.3, the information provided on format ED-1 was also included as part of the information displayed on the remaining three formats shown in Figure 6-2. The characteristics of format ED-1 are presented in Table 6-3.

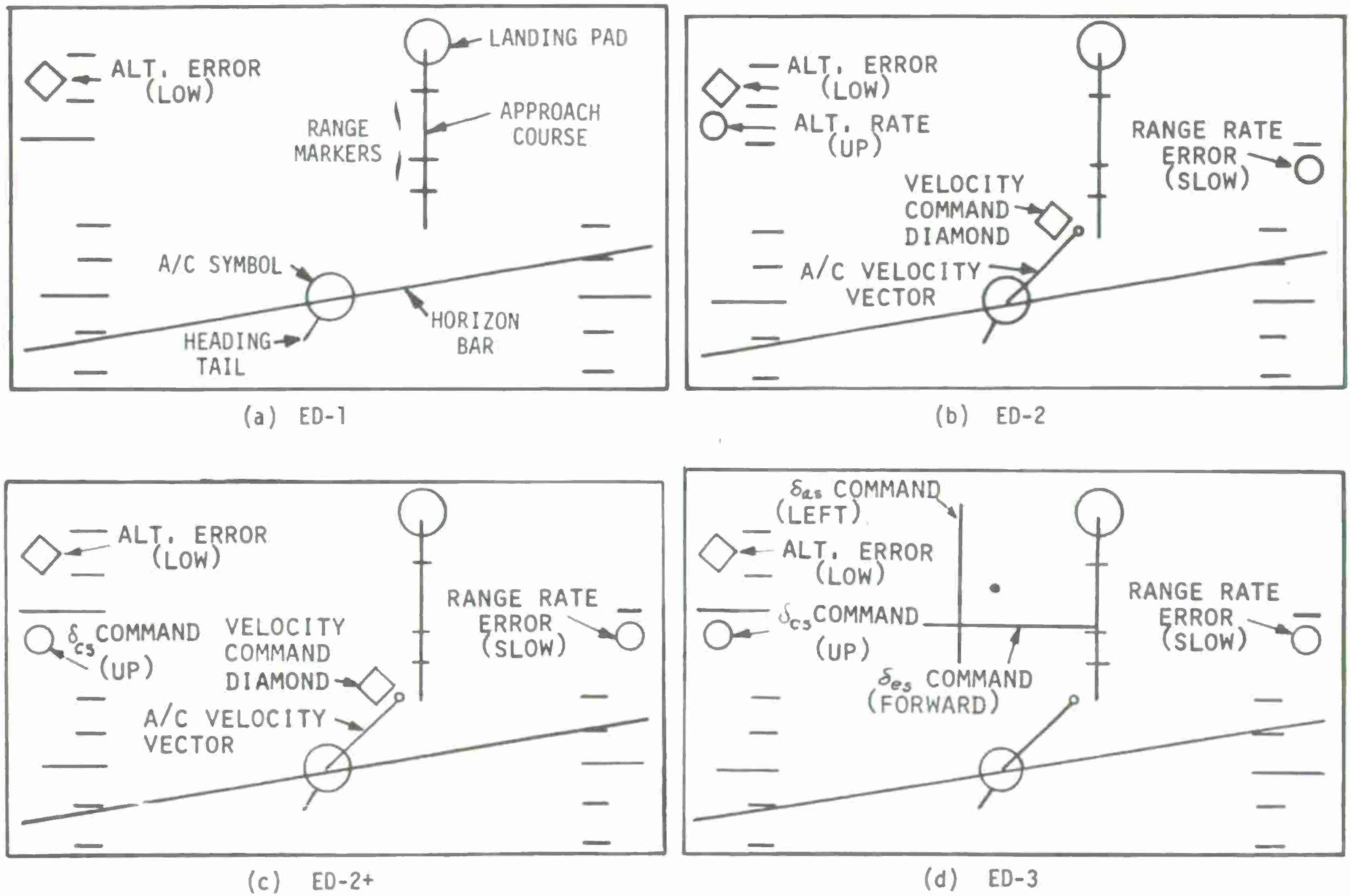


Figure 6-2 ELECTRONIC DISPLAY FORMATS

Table 6-3

CHARACTERISTICS OF DISPLAY FORMAT ED-1

Information Category	Information	Symbol(s)	Sense/Scaling (1 cm = 0.85 degree of arc at pilot's eye)
Orientation	Pitch, Roll	Fixed A/C symbol and attitude indices, moving horizon bar	one-to-one with real world; 10° index increments
	Heading	Tail of fixed A/C symbol with respect to approach course	one-to-one with real world
Position	Altitude error	Diamond and fixed indices	"fly to" sense, i.e., diamond represents desired altitude, reference represents actual altitude; ± 100 ft full scale (±1.5 cm); 50 ft intervals
	Descent progress	Landing pad	diameter increases linearly with de-creasing altitude (1 cm @ 875 ft AGL 2 cm @ 100 ft AGL)
	Horizontal Position	Fixed A/C symbol, moving landing pad/approach course symbol	continuously increasing sensitivity with range (100 ft/cm in hover); diameter of A/C symbol = 1 cm
	Approach Progress	Fixed A/C symbol, three moving range markers to indicate important points on approach	12,000 ft 8,000 ft 800 ft

Adhering to the principles of integrated display design adopted for the experiment, the information displayed on format ED-1 in general moves with respect to fixed symbols representing the aircraft:

- pitch and roll - an "inside-out" display of an artificial horizon.
- vertical position - an altitude error diamond representing the desired altitude which moves with respect to a fixed reference representing the aircraft.
- horizontal position - a landing pad/approach course symbol which translates with respect to the fixed aircraft symbol.

During the approach to the hover, aircraft heading changes with respect to the desired approach course are indicated by the rotation of the tail of the aircraft symbol; the approach course symbol does not rotate. This method of displaying aircraft orientation was used by Dukes in Reference 14; in a preliminary ground simulator experiment (Appendix III) this "earth-referenced" display was found to be more meaningful for the approach phase of the task than a "heading-referenced" display in which the aircraft tail remained fixed and the landing pad/approach course symbol both translated and rotated on the display to indicate position and orientation, respectively. However, preliminary flight testing revealed that the heading-referenced display mode was required for the hover phase of the task. (The implementation of this shift in display coordinate systems is discussed later in this section.)

Vertical situation is displayed to the pilot in the form of an altitude error rather than as absolute values of actual and command altitudes. The altitude error is computed on-board as $\epsilon_z = z_{e_c} - \hat{z}_e$ where z_{e_c} is the guidance command defined in Section 4.5 and $\hat{z}_e$ is the smoothed estimate of height which is a complementary filter output. The location and sense of the altitude error diamond was selected for a more natural association with the evaluation pilot's primary vertical controller -- the collective stick located on his left-hand side. The scaling of this parameter ($\sim$67 ft/cm) was determined as a result of the preliminary simulator experiment and verified in flight; the scaling remained constant throughout the task.

Horizontal situation is displayed in the form of command and actual position; although no command range exists during the approach (i.e., no time scheduling), a "commanded" lateral position is determined by the relative location of the aircraft and course symbols. In the hover, the center of the pad (origin of the approach course symbol) indicates the command horizontal position. Although contrary to the principle of displaying errors vice absolutes, this display technique was required to provide sufficient information regarding both current position and progress along the approach. The resulting format is directly comparable to the NASA Langley work with a moving map (Reference 7), the initial ground simulator experiment (Reference 12), the ITED format advocated

by Dukes (Reference 14), and the RAE display format used in the CL-84 program (Reference 16).

To provide position information throughout the entire approach beginning at a range of ~ 4 miles but also to ensure sufficient position resolution for the hover phase of the task, a scaling technique which resulted in a displayed position sensitivity inversely proportional to the range was adopted. The relationship between displayed position (d) and actual position (X) is as follows:

$$d = \frac{K_d X}{|\hat{X}_e| + K} \qquad \text{where } K_d \text{ and } K \text{ are constants. } X \text{ is } \hat{X}_e \text{ or } \hat{Y}_e. \qquad (6\text{-}1)$$

Hence for $|\hat{X}_e| >> K$, $\quad d \doteq \dfrac{K_d X}{\hat{X}_e}$

and for $|\hat{X}_e| << K$, $\quad d \doteq \dfrac{K_d X}{K}$

Therefore the constant K_d was chosen to yield a maximum displayed range of 6 cm, i.e., K_d = 6 cm, and the ratio K_d/K was selected to provide a 100 ft/cm scaling in the hover (K_d/K = .01 cm/ft; K = 600 ft). The final relationship was

$$d = \frac{6X}{|\hat{X}_e| + 600} \quad (cm)$$

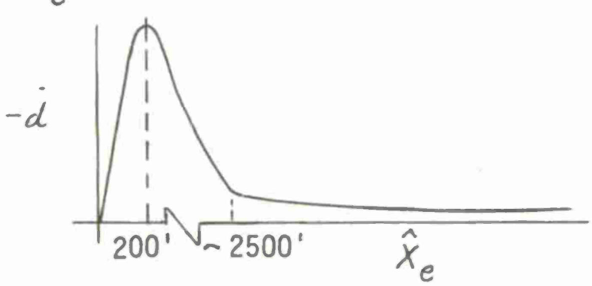
A possible problem with this method of display scaling is the disparity between the displayed rate of change of position and the actual rate of change. Although no attempt was made to have the pilot estimate rates of change by the movements of position symbols, unnatural motions of these symbols might be disconcerting. From Equation (6-1); assuming $\hat{X}_e > 0$:

$$\dot{d} = \frac{K_d}{(\hat{X}_e + K)^2}\left[(\hat{X}_e + K)\dot{X} - X\dot{\hat{X}}_e\right]$$

As an example, let $X = \hat{X}_e$; therefore;

$$\dot{d} = K_d K \dot{\hat{X}}_e / (\hat{X}_e + K)^2$$

For the selected deceleration profile $\left(i.e., \dot{x}_e = -\sqrt{2\ddot{X}_e X_e}\right)$ the relationship between $\dot{d}$ and $\hat{X}_e$ is as illustrated below:



The characteristics of the displayed range rate are therefore very similar to those of the angular rate of the line of sight of an object on the ground observed by the pilot ($\dot{R}_a$). $\dot{R}_a$ is equal to the ratio of $\hat{\dot{x}}_e$ to the altitude AGL (h); substituting the appropriate expressions for $\hat{\dot{x}}_e$ and h for each of the basic elements of the evaluation task:

- for level flight, constant speed: $\dot{R}_a$ = constant
- for a constant-angle descent, constant speed: $\dot{R}_a \sim (1/\hat{x}_e)$
- for a constant-angle descent, constant deceleration: $\dot{R}_a \sim (1/\sqrt{\hat{x}_e})$
- for level flight, constant deceleration: $\dot{R}_a \sim \sqrt{\hat{x}_e}$

Furthermore, near the hover ($\hat{x}_e \ll K$), this scaling technique yields the desirable characteristic of a rate of change of displayed position directly proportional to the actual rate. The only obvious difference between the characteristics of $\dot{d}$ and $\dot{R}_a$ involves the range at which the maximum value of each occurs. The maximum value of $\dot{R}_a$ occurs at the flare point ($\sim$750 ft); it can be shown that the maximum value of $\dot{d}$ occurs at a range of $K/3$, i.e., at 200 ft. This disparity, however, is far outweighed by the advantages of the chosen horizontal position scaling technique.

Information concerning approach progress is displayed through the use of the range markers and the expanding landing pad symbol. The range markers are located at three important points of the approach: glide slope intercept ($\sim$12,000 ft), zero-wind deceleration commencement (8,000 ft), and the flare point ($\sim$750 ft). The aircraft has reached one of these points in the approach when the leading edge of the aircraft symbol is intersected by that point's range marker. Descent progress is indicated by the diameter of the expanding landing pad symbol; the diameter increases linearly with decreasing altitude so that, at $\sim$875 ft AGL, the pad is the same size as the aircraft symbol (1 cm diameter) and at 100 ft AGL its diameter is twice that of the aircraft symbol. A symbol of this type was used on the RAE display format investigated in the CL-84 program as a height and/or height rate cue; although the symbol was not found to be particularly useful in the CL-84 experiment (Reference 16), it was adopted for this experiment to avoid unnecessary clutter on the display early in the approach, to display the necessary horizontal position information to the pilot with sufficient resolution for the hover phase, and to provide some indication of descent progress on the glide slope.

The next level in the hierarchy of displayed information resulted from the addition of velocity information to the ED-1 format which produced the ED-2 and ED-2+ formats illustrated in Figure 6-2. Four additional symbols were added to provide velocity information to the pilot in three dimensions; the function and characteristics of these symbols are summarized in Table 6-4.

Table 6-4

CHARACTERISTICS OF DISPLAY FORMAT ED-2 AND ED-2+

Information Category	Information	Symbol(s)	Sense/Scaling (1 cm = 0.85 degree of arc at pilot's eye)
Orientation	Same as ED-1 Format (Table 6-2)		
Position	Same as ED-1 Format (Table 6-2)		
Velocity	Horizontal Velocity Status	Velocity Vector	20 kt/cm - approach 5 kt/cm - hover
	Horizontal Velocity Command	Velocity Command Diamond	20 kt/cm - approach 5 kt/cm - hover
	Longitudinal Velocity Error	Right-Hand Circle	Low $\Longrightarrow$ slow; 50 ft/sec/cm
	Vertical Velocity Deviation (ED-2 only)	Left-Hand Circle	Low $\Longrightarrow$ actual descent rate > command; increasingly sensitive scaling with duct angle (6.7 ft/sec/cm @ $\lambda = 90^\circ$; 33.3 ft/sec/cm @ $\lambda = 0^\circ$)
Control Director (ED-2+ Only)	Collective Control Director	Left-Hand Circle	"Fly-away" sense; $\pm$ 1.5 cm full scale

One of the principles of the display design philosophy used for this experiment is that rate information, when displayed, be displayed explicitly in such a manner as to provide the pilot with easily comprehensible lead information. Both the velocity vector and altitude rate deviation symbols were added to the display with this principle in mind.

The concept of a velocity vector has been used in several VTOL display formats; see, for example, References 14 and 16. However the use of the vector in conjunction with a separate velocity command symbol represents a new approach to the display of velocity status and command. The RAE CL-84 display format (Reference 16) contained a "guidance vector" whose length, during the deceleration, was proportional to the square of range rate and whose position in azimuth with respect to the landing pad symbol was determined by director-like logic; the pilot's task was to overlay the tip of the guidance vector on the landing pad symbol in order to follow the selected horizontal trajectory. On the other hand, Dukes (Reference 14) uses a true velocity vector with no command symbol for his precision hover format. It was decided, in order to preserve the hierarchy of displayed information required for the experiment and to avoid the loss of status information inherent in the integration of various levels of information into a single display element, that the velocity vector should represent true horizontal velocity and that a separate symbol should indicate the command velocity. The velocity vector and velocity command diamond are driven by guidance signals described in Section IV. The pilot's task is to center the tip of the velocity vector inside the diamond in order to maintain the selected horizontal velocity profile. The maximum groundspeed on the approach ($\sim$100 Kt) determined the scaling of the velocity vector and command diamond (20 Kt/cm); however, both the preliminary simulator experiment and practice evaluations revealed that this scaling was too coarse for the hover phase of the task. As a result, a change to a "hover mode" scaling of the vector and diamond, which increased their sensitivity by a factor of four, was effected under pilot control at or near the hover.

A velocity error display is located on the right hand side of the format; this symbol displays the error between the command and actual heading-referenced velocities derived in Section IV, i.e., $\epsilon_{\dot{x}_h} = \dot{X}_{h_c} - \hat{\dot{X}}_h$, and is included as backup information in accordance with the principle of displaying guidance errors rather than absolutes where possible.

With the ED-2 format, the pilot's display task in the vertical plane is similar to the horizontal task in that he is required to center the altitude rate deviation circle in the altitude error diamond in order to null out height errors properly. A similar form of vertical display is contained in the ITED format used by Dukes in his helicopter display research (Reference 14). This portion of the display is considered to be especially crucial for V/STOL aircraft because of the difficulty of the vertical tracking task caused by the low values of natural height damping inherent in this type of aircraft at low speed and the cross-coupling between speed and flight path control which occurs in these aircraft at higher approach speeds. Ample evidence of this display-related height control problem is supplied by the results of the Phase

One CL-84 program (References 16 and 17). The display format in that program included a central height error display (glide slope brackets) and a peripheral thermometer-type vertical speed display on the right-hand side, and major problems with altitude control occurred throughout the entire task. The results of that program revealed possible display deficiences which led to the poor height-keeping performance, including:

- the central location of the glide slope brackets which caused them frequently to be misinterpreted as a pitch stick director
- the need for a power lever director symbol on the left-hand side of the display for more natural association with the power lever on the pilot's left
- the separated vertical position and rate information display.

The height information display of the ED-2 electronic display format represents an attempt to alleviate similar difficulties in height control through careful display format design. In particular, the following techniques were employed:

- symbol location - height and height rate information are located on the left-hand side of the display for a clear association with the primary vertical controller, the collective stick
- error display - only height error (ϵ_z) and height rate deviation ($\epsilon_{\dot{z}} = \dot{z}_{e_c} - \hat{\dot{z}}_e$) are displayed; the pilot is free of the requirement to determine the error through a comparison of two absolute quantities
- sense of symbol motion - the sense of the height rate deviation symbol was selected so that the symbol moves with the pilot's collective stick input, i.e., an up collective input results in a reduced descent rate and hence an upward motion of the symbol; this sensing convention allows the pilot to position the circle inside the altitude error diamond in a logical manner
- scaling of symbol motion - the sensitivity of the height rate deviation symbol increases linearly with duct angle to compensate for the reduction in natural height damping of the aircraft during the conversion to powered lift.

In a further attempt to improve the control of altitude errors, a collective director symbol (VTAB) is substituted for the height rate deviation symbol in

the ED-2+ format. Although resulting in a "mixed" format in the display hierarchy for the experiment, a collective director may be a requirement for those VTOL aircraft exhibiting low values of height damping, and hence the ED-2+ format was included for investigation. With this format, the pilot's display task is to place the collective director circle on the fixed reference in order to satisfy the director laws; the sense of the symbol motion is such that an upward collective input results in an upward symbol motion. The logic which determines the dynamics of the collective control director is presented in Section 6.5.

The design of the fourth display format, ED-3 (Figure 6-2), substituted longitudinal and lateral stick director elements (HBAR and VBAR, respectively) and a fixed reference for the velocity command diamond of format ED-2+. The central location of the director bars corresponds to the location of the center stick, and the sense of both director elements is "fly to"; that is, HBAR down and VBAR right command forward and right center stick inputs, respectively. The logic for the HBAR and VBAR director elements is presented in Section 6.5. A valid argument against many director displays is that they attempt to enhance performance by integrating individually important pieces of status information on a single display element which requires constant attention, thereby reducing both the information and time available for the pilot to perform his function as system monitor. For this reason, the ED-3 format, in addition to providing three-axis control director information, also retains the status information found in the ED-2+ format (Table 6-4).

A fifth display format (ED-1/FD) consists of the ED-1 electronic display format and three-axis control director information displayed on the electromechanical ADI; this display configuration corresponds to NASA Langley's CH-46 format (Reference 5) and was included both to test their results and to reinforce the requirement for integrated displays. The logic driving the electromechanical director elements is identical to that used in the ED-3 format; a lead-lag circuit ($s+1/ s+10$) is used to compensate for the one-second time constant lag exhibited by the electromechanical collective director element.

Most of the display formats also include a fourth director element, the separate configuration change director light (Figure 6-1), the implementation of which is discussed in the following subsection. However, a brief investigation of the effects resulting from its absence was also conducted to verify the results of the preliminary simulator study which indicated an intolerable pilot workload without it.

Two alterations in the display formats occur at or near the hover under pilot control. The push-button control which selects the automatic turn coordination (ATC) or the heading hold (HH) directional modes also selects the reference frame for the horizontal situation display. When ATC is selected, an earth-referenced system ("approach-course-up") is used for the display of horizontal position, velocity, and command velocity. When HH is selected near the hover, an aircraft heading-referenced system ("heading up") is used in

which the tail of the aircraft symbol is fixed and the landing pad/approach course symbol both translates and rotates to indicate position and orientation.

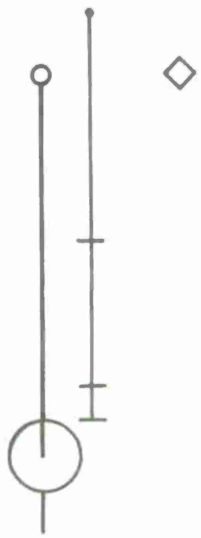
The reference systems and axis system transformations are defined in Section IV. As was discussed earlier, the heading-referenced display proved to be more effective in conveying to the pilot the information required for the hover phase of his task; using this display mode, he was able to exert direct control over the displayed horizontal velocity vector through his center stick at any heading without the required mental axis transformation from the earth-referenced system to the aircraft system. However, the earth-referenced system was preferable for the approach; the pilot experienced some disorientation in the preliminary simulator study when the approach course symbol rather than the aircraft tail rotated in response to heading changes during the localizer acquisition phase. The point in the approach at which the shift in display coordinate systems took place was selected based upon three factors: that the shift be under pilot control, that it occur near the hover, and that it not increase the pilot's mental workload through the presence of another cockpit switch to be operated. Since the pilot used the heading hold directional control mode in hover for control of yaw rate and heading, integrating the switch in display reference with the switch in control mode was logical.

A second display variation for the hover task is the discrete increase in sensitivity of the velocity vector and velocity command diamond which was selected by the pilot by voice command to the radar operator; this "hover mode" sensitivity resulted from the transmittal of the discrete telemetry signal for the final manual scale change discussed in Section 4.2. The effect of these display alterations is illustrated in Figure 6-3 for the horizontal position and velocity information portion of format ED-2 and ED-2+.

6.5 SYNTHESIS OF CONTROL DIRECTOR LOGIC

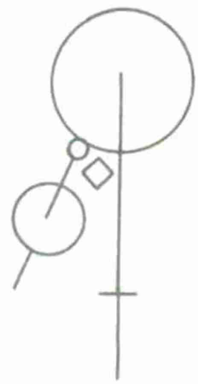
The synthesis of the logic driving the control director elements of the ED-3 and ED-1/FD display formats constituted a major portion of the display design process. The principles which guided the control director design were:

- Design condition - the precision hover was the critical portion of the task and hence the design condition for the control director.
- Simplified logic - an attempt was made to minimize the need for logic switching, error limiting, and gain scheduling.
- Use of manual control theory - the response of the director elements to control inputs must be acceptable to the pilot and yet not significantly degrade overall system performance.
- Four-axis director - each director element commanded a single control input; therefore, in general, four director elements



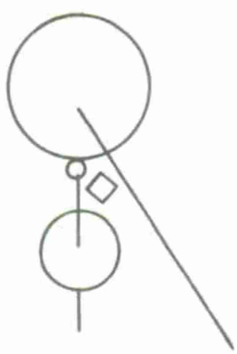
(a)

AT GLIDE SLOPE INTERCEPT, V = 100 kt, ~1000 ft TO LEFT OF APPROACH COURSE; HEADING PARALLEL TO APPROACH COURSE; NORMAL SCALING, ATC SELECTED



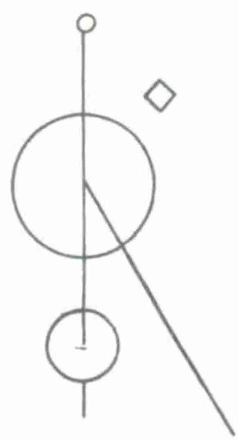
(b)

LEVEL APPROACH TO HOVER, V = 20 kt, ~100 ft TO LEFT OF APPROACH COURSE WITH ~200 ft TO TOUCHDOWN POINT; HEADING 030 WITH RESPECT TO APPROACH COURSE; NORMAL SCALING, ATC SELECTED



(c)

SAME SITUATION AS (b); HH SELECTED



(d)

SAME SITUATION AS (c); HOVER MODE SCALING

Figure 6-3 ED-2/2+ HORIZONTAL SITUATION/COMMAND INFORMATION DISPLAY FORMAT

were required for the task: longitudinal stick, lateral stick, collective stick (thrust magnitude), and duct angle (thrust direction).

The final version of the control director logic was a result of preliminary analysis, extensive ground simulation, and in-flight testing. Several techniques for control director design based upon the theory of manual control were examined; the design techniques vary primarily in the assumed characteristics of the human pilot, for example:

- a design based upon the closed-loop system time response for an assumed pilot model (Reference 40)
- a design based upon prescribed open-loop frequency domain characteristics that will be desirable to the pilot (Reference 41)
- a design on the basis that the pilot acts as a pure feedback gain in an optimal controller (Reference 42)
- a design involving an optimal system compensated for the pilot's inherent time delay (Reference 35)
- a design based upon frequency separating the director information presented to the pilot from that sent to an automatic control system (Reference 22).

A technique, based upon classical control theory, used by Systems Technology, Inc. (STI) (Reference 41, for example) was finally adopted. The technique involves the fulfillment of several guidance- and pilot-oriented requirements. The pilot-oriented requirements are based upon the STI "crossover" pilot model; basically, the director element must be designed so that its open-loop response is proportional to the integral of the pilot's control input in the frequency region of control in order to ensure pilot acceptability and good closed-loop system characteristics for a wide range of pilot gains. Therefore, in order to achieve this K/s-like open-loop response, the director characteristics in general vary as a function of the generic controlled vehicle characteristics described in Section V. A compatible supplementary requirement, based upon the experience of NASA Langley (Reference 5), was that control position not be used as a feedback variable to the display: therefore the proper airplane response, not control input is required to center each control director element. The following portion of this subsection describes the design process for the three control director elements of the ED-3 and ED-1/FD display formats, which are:

- Horizontal bar (HBAR) – longitudinal stick (δ_{es}) command
- Vertical bar (VBAR) – lateral stick (δ_{as}) command
- Vertical tab (VTAB) – collective stick (δ_{cs}) command

Following this discussion, the logic for the fourth control director element, the configuration change director, is presented.

6.5.1 Longitudinal Control Director Design

The design of optimized control directors for the longitudinal degrees of freedom of a V/STOL aircraft during a decelerating transition landing approach according to the techniques of Reference 41 will in general require a substantial degree of gain scheduling and logic switching to account for the wide variation in controlled vehicle characteristics through the conversion from aerodynamic lift to powered lift. It was the intent from the outset to design and implement simplified flight director logic for each of the three basic longitudinal control systems to be investigated: rate augmentation, attitude augmentation, and decoupled velocity control (DVC) systems; and to investigate the suitability of the resultant logic in ground simulation and flight testing.

Since a control director by its very nature forces a particular control technique to be adopted by the pilot, the first decision in the design process concerned the selection of a single control technique which would be suitable for the entire evaluation task, i.e., from level flight at 100 Kt through a descending transition to and including the hover. This decision is more involved in the case of the vectored-thrust V/STOL aircraft than is the corresponding selection of a control technique for a helicopter during decelerating approaches from low initial airspeeds (~45 Kt) as were conducted by NASA Langley for example (Reference 5); in that program, since the approach speeds were less than the speed for minimum power, the director elements commanded flight path control by collective pitch and speed control by longitudinal cyclic (the "backside of the power curve" control technique). In addition, the required deceleration profile was tailored to the helicopter characteristics, requiring a constant positive increment in pitch from the trim attitude to begin and maintain the commanded deceleration; since an attitude command system was implemented in pitch, the deceleration maneuver was essentially accomplished by a positive increment in longitudinal cyclic stick position. For the vectored-thrust V/STOL aircraft, complications in the control technique arise for two primary reasons:

- Because of the transition from frontside to backside of the power-required curve characteristics, a decelerating approach from 100 Kts of airspeed may require a shift in control technique in mid-conversion from the CTOL technique (thrust magnitude control of airspeed) to the VTOL technique (thrust magnitude control of flight path).
- The longitudinal control problem now involves three controllers: pitch, thrust magnitude, and thrust direction.

The Harrier aircraft typically performs VFR decelerating approaches from 90 Kts of airspeed. A preferred control technique for this maneuver involves the

immediate rotation of the thrust vector to the vertical by a position controller; thrust magnitude is then used for flight path control while the pitch stick is used to achieve a near-constant pitch attitude through the transition (Reference 43). Jet-lift V/STOL aircraft, however, enjoy the benefit of less restrictive transition boundaries than tilt-thrust aircraft such as the X-22A and CL-84. For this latter type of VTOL, the rotation of large aerodynamic surfaces involved in changing thrust direction limits the speed with which rotation can occur, and hence the "instantaneous" direct lift control with thrust is not available. For example, in a simulation of the Harrier approach profile (Reference 16), the pilots of the CL-84 experienced the cross-coupling between speed and flight path control induced by the slower thrust vector rotation from near-horizontal to the vertical required to remain within the aircraft's wing stall boundaries.

In spite of this known problem with changing control technique requirements through the transition, the "backside" (use of thrust magnitude for flight path control) control technique was used as the foundation for the control director design in this experiment. This decision was based on the importance of the level off and final deceleration to a hover, parts of the task for which the backside technique is appropriate, and on the desire to simplify the flight director logic. This decision required that collective pitch be used for flight path/altitude control throughout the evaluation task; two candidate controllers of speed/longitudinal position were therefore available: thrust vector angle (duct angle) and pitch attitude. In the initial ground simulator experiment (Reference 12), a single director element commanded pitch stick and duct rotation inputs to achieve the desired velocity profile; typically, the pilot would use duct rotation, at a constant 5 deg/sec rate controlled by an ON-OFF switch, to correct large director errors and pitch stick inputs for finer control of the director bars. This technique worked satisfactorily for the deceleration; however, the pilot's control problem was complicated by the lack of precise indications of the point to begin the deceleration (requiring duct rotation in addition to pitch stick inputs for speed control) and of the hover condition (requiring pitch stick only for position control). On a more general basis, the underlying philosophy of control director design is to provide a separate director for each controller. It was therefore decided to use separate director elements for duct angle and pitch stick inputs with duct angle used as a coarse speed control and pitch attitude as a vernier speed/position control. Although a continuous director element is suitable for a continuous controller such as the pitch stick, the ON-OFF control of duct rotation requires a discontinuous director element; as a result, the horizontal control director bar (HBAR) commands pitch stick inputs only while a separate ON-OFF director light, described later in this subsection, commands duct rotation inputs.

In general the HBAR control director logic is expressed as follows:

$$HBAR = K_{\dot{x}} \epsilon_{\dot{x}_h} + K_\theta \theta_{WO} + K_q q = K_{\dot{x}} (\dot{x}_{h_c} - \hat{\dot{x}}_h) + K_\theta \theta_{WO} + K_q q \quad \text{(volts)}$$

A heading-referenced velocity error term is used to allow valid control director commands for the phases of the task involving large heading angles with respect to the approach course: the localizer acquisition and the final approach/hover with a crosswind component. A 5-second washout on the pitch attitude term corresponding to the drag damping of the basic X-22A ($X_u \sim -0.2\ \text{sec}^{-1}$) is used to prevent standoff errors in speed tracking caused by non-zero values of trim pitch attitude. The body axis pitch rate (q) is used instead of the Euler angular rate ($\dot{\theta}$) to avoid the additional computations involved in axis system transformations; this simplification is based upon the assumption of small bank attitudes and body-axis yaw rates. The values of the director gains K_θ and K_q vary as a function of controlled vehicle characteristics (type of control augmentation) but do not vary with flight condition for each type. Their values were selected in order to achieve a K/s-like HBAR/$\delta_{es}(s)$ transfer function in the pilot's frequency region of control for the assumed hover characteristics of the three longitudinal control systems investigated.

For the attitude augmentation system, the approximate hover transfer functions of interest are:

$$\left.\begin{aligned} \frac{\dot{X}}{\delta_{es}}(s) &\cong \frac{g M_{\delta_{es}} (-Z_w)}{(-Z_w)(-X_u)[\zeta_\theta ; \omega_\theta]} \\ &\text{and} \\ \frac{\theta}{\delta_{es}}(s) &\cong \frac{M_{\delta_{es}} (-Z_w)(-X_u)}{(-Z_w)(-X_u)[\zeta_\theta ; \omega_\theta]} \end{aligned}\right\} \qquad (6\text{-}2)$$

where

$$\frac{K}{\left(\frac{1}{\tau}\right)[\zeta ; \omega]} = \frac{K}{\left(s+\frac{1}{\tau}\right)\left(s^2+2\zeta\omega s+\omega^2\right)} \quad \text{for simplicity}$$

and ζ_θ, ω_θ are the characteristics of the attitude control pre-filter model. Since the commanded groundspeed is a linear function of position in the hover ($\dot{X}_c = K_X X$, see Section IV), the HBAR/$\delta_{es}(s)$ transfer function may be written as follows, neglecting the contribution of the washout:

$$\frac{HBAR}{\delta_{es}}(s) = -K_{\dot{X}}\left(\frac{s-K_X}{s}\right)\left(\frac{\dot{X}}{\delta_{es}}(s)\right) + K_{\dot{\theta}}\left(s+\frac{K_\theta}{K_{\dot{\theta}}}\right)\left(\frac{\theta}{\delta_{es}}(s)\right) \qquad (6\text{-}3)$$

Combining Equations (6-2) with Equation (6-3) and setting the constant $K_X = X_u$ we have:

$$\frac{HBAR}{\delta_{es}}(s) = \frac{K_{\dot{\theta}} M_{\delta_{es}} (s-X_u)\left(s^2+\frac{K_\theta}{K_{\dot{\theta}}}s-\frac{gK_{\dot{X}}}{K_{\dot{\theta}}}\right)}{s(s-X_u)(s^2+2\zeta_\theta\omega_\theta s+\omega_\theta^2)} \cdot \frac{(s-Z_w)}{(s-Z_w)}$$

Therefore in order to create a wide frequency band of K/s-like open-loop response, the gain ratios should be set as follows:

$$K_x = X_u \simeq -0.2 \qquad \frac{\text{ft/sec}}{\text{ft}}$$

$$\frac{K_{\dot{x}}}{K_{\dot{\theta}}} = -\frac{\omega_\theta^2}{g} = -\frac{(2)^2}{32.2} = -0.124 \qquad \frac{\text{rad/sec}}{\text{ft/sec}}$$

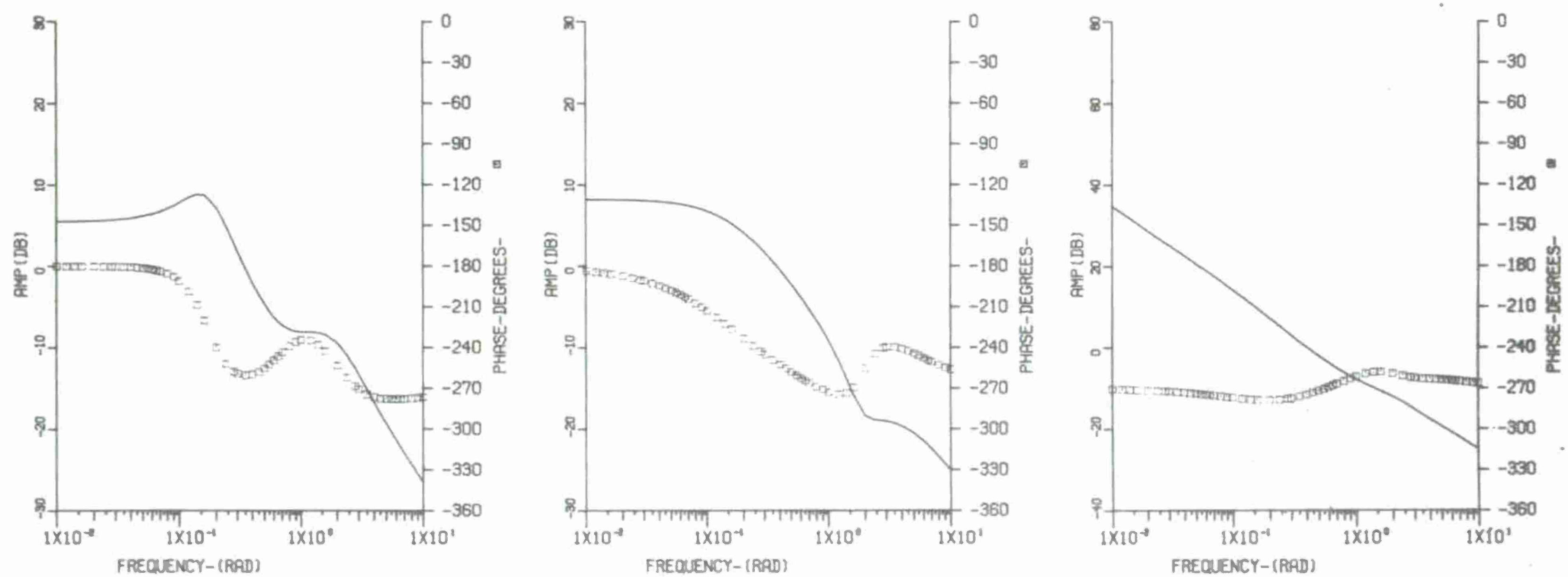
$$\frac{K_\theta}{K_{\dot{\theta}}} = 2\zeta_\theta \omega_\theta = 2(.7)(2) = 2.8 \qquad \frac{\text{rad/sec}}{\text{rad}}$$

The individual values of the gains were determined by the selection of $K_{\dot{x}}$ in the preliminary simulator study; these values are presented in Table 6-12 at the end of this section. The actual HBAR/$\delta_{es}(s)$ transfer functions for three flight conditions (λ = 15°, V = 100 Kt; λ = 50°, V = 65 Kts; λ = 90°, V = 0 kts) are presented in Table 6-5; these transfer functions are based upon the controlled vehicle characteristics presented in Section V. The corresponding Bode diagrams are presented as Figure 6-4.

Table 6-5

HBAR/$\delta_{es}(s)$ TRANSFER FUNCTIONS FOR ATTITUDE AUGMENTATION IN FORM $K\left(\frac{1}{\tau}\right)[\zeta;\omega]$

Flight Condition (λ; V)	HBAR/$\delta_{es}(s)$ ~ volt/in (±5 volts full scale)
15°; 100 Kt	$\frac{[0.7;4.0]}{[0.7;2.0]} \cdot \frac{-0.44(0.2)[0.65;0.71](4.64)}{(0.2)(0.23)(0.55)[0.75;4.1]}$
50°; 65 Kt	$\frac{[0.7;4.0]}{[0.7;2.0]} \cdot \frac{-0.59(0.21)(0.45)[0.37;1.94]}{(0.2)(0.16)(0.5)[0.72;4.45]}$
90°; 0 Kt	$\frac{[0.7;4.0]}{[0.7;2.0]} \cdot \frac{-0.57(0.12)(0.18)(0.31)[0.83;1.67]}{(0)(0.12)(0.17)(0.2)[0.74;4.29]}$



(a) $\lambda = 15^0$ (b) $\lambda = 50^0$ (c) $\lambda = 90^0$

Figure 6-4 HBAR/δ_{es}(s) BODE PLOT - ATTITUDE SYSTEM

It can be seen from an inspection of Table 6-5, that the HBAR/δ_{es} transfer function for the λ = 15° case exhibits K/s-like characteristics only in a small frequency band (~0.2 - 0.6 rad/sec); however, with increasing duct angle, this frequency band opens up to include higher frequencies. The lower order of the λ = 15° and 50° transfer functions numerators and denominators is due to the absence of an explicit position feedback term.

The design technique proceeded in a similar fashion for the rate augmentation control system. In this case, the hover transfer functions of interest are:

$$\left.\begin{aligned} \frac{\dot{x}}{\delta_{es}}(s) &\doteq \frac{g M_{\delta_{es}}(-Z_w)}{(-Z_w)(-M_q)[\zeta;\omega]} \\ \frac{\theta}{\delta_{es}}(s) &\doteq \frac{M_{\delta_{es}}(-Z_w)(-X_u)}{(-Z_w)(-M_q)[\zeta;\omega]} \end{aligned}\right\} \qquad (6\text{-}4)$$

Combining Equations (6-4) with Equation (6-3),

$$\frac{HBAR}{\delta_{es}}(s) = \frac{K_{\dot{\theta}} M_{\delta_{es}}\left[s^3 + \left(-X_u + \frac{K_\theta}{K_{\dot{\theta}}}\right)s^2 - g\frac{K_{\dot{x}}}{K_{\dot{\theta}}}s + g\frac{K_x K_{\dot{x}}}{K_{\dot{\theta}}}\right](s - Z_w)}{s(s - M_q)(s^2 + 2\zeta\omega s + \omega^2)(s - Z_w)}$$

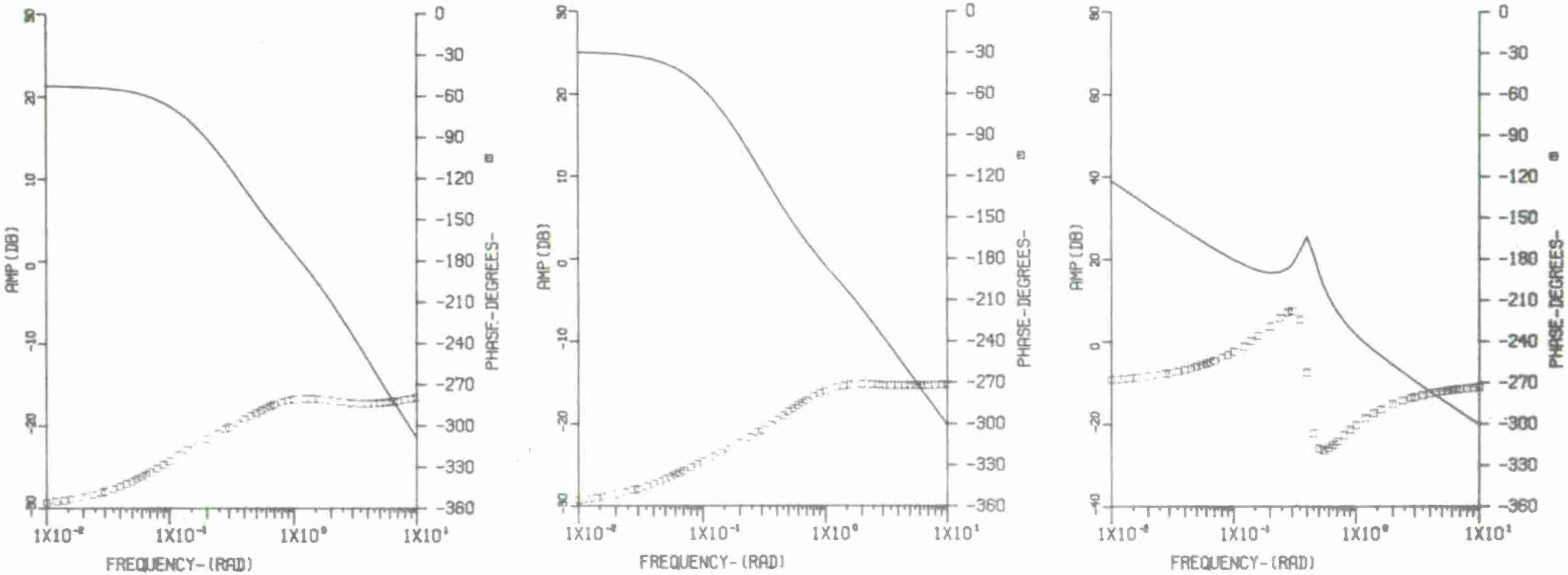
To create a wide frequency band of K/s-like characteristics and to improve the stability of the closed-loop system, the numerator cubic was set equal to the quantity $(s - M_q)(s^2 + 2(.7)\omega s + \omega^2)$. The required gain ratios were therefore:

$$K_x \doteq -\frac{\omega}{2(0.7)} = -\frac{0.4}{1.4} = -0.28 \qquad \frac{\text{ft/sec}}{\text{ft}}$$

$$\frac{K_{\dot{x}}}{K_{\dot{\theta}}} \doteq -\frac{2(0.7)\omega(-M_q)}{g} = -\frac{2(0.7)(0.4)(3.0)}{32.2} = -0.053 \qquad \frac{\text{rad/sec}}{\text{ft/sec}}$$

$$\frac{K_\theta}{K_{\dot{\theta}}} \doteq -M_q + X_u + 2(0.7)\omega \doteq -M_q \doteq 3.0 \qquad \frac{\text{rad/sec}}{\text{rad}}$$

The $K_{\dot{x}}$ director gain was held at its value for the attitude augmentation system; K_θ and $K_{\dot{\theta}}$ were then uniquely determined. The final director gains are presented in Table 6-12; the actual transfer functions are presented in Table 6-6 and the corresponding Bode plots are found in Figure 6-5.



(a) $\lambda = 15^{\circ}$ (b) $\lambda = 50^{\circ}$ (c) $\lambda = 90^{\circ}$

Figure 6-5 HBAR/δ_{es}(s) BODE PLOT - RATE SYSTEM

Table 6-6

HBAR/δ_{es} (s) TRANSFER FUNCTIONS FOR RATE AUGMENTATION IN FORM $K\left(\frac{1}{\tau}\right)[\zeta;\omega]$

Flight Condition $(\lambda; V)$	HBAR/$\delta_{es}(s)$ ~ volts/in (±5 volts full scale)
15°; 100 Kt	$\dfrac{-0.8(0.19)[0.94\,;\,0.56](4.84)}{(-0.12)(0.2)(0.31)(0.93)(2.9)}$
50°; 65 Kt.	$\dfrac{-0.98(0.22)(0.35)(1.15)(2.49)}{(-0.092)(0.18)(0.2)[0.94\,;\,1.95]}$
90°; 0 Kt	$\dfrac{-0.99(0.12)(0.17)[0.77\,;\,0.42](2.95)}{(0)(0.12)(0.2)[0.1\,;\,0.41](2.94)}$

Because of the wide frequency region of K/s-like characteristics demonstrated in Table 6-6 the constant-gain flight director should be acceptable to the pilot for all flight conditions in the evaluation task.

The HBAR director design for the DVC system represented a departure from the director design philosophy because of the manner in which the DVC system was implemented. As discussed in Section V, the duct rotation switch controlled longitudinal velocity while the pitch stick performed a trimming function only. Because of the augmented and decoupled longitudinal velocity response to duct angle inputs, only the velocity error term, $\epsilon_{\dot{x}_h}$, was fed back to HBAR with $K_{\dot{x}}$ set equal to its value for the other longitudinal systems. The resultant HBAR/$\delta_\lambda(s)$ transfer functions are presented in Table 6-7; the corresponding Bode diagrams are found in Figure 6-6.

The collective control director (VTAB) logic is expressed as follows:

$$\text{VTAB} = K_z\epsilon_z + K_{\dot{z}}(\lambda)\,\epsilon_{\dot{z}} \qquad \text{(volts)}$$

For all the longitudinal control systems, the approximate hover transfer function of interest is:

$$\frac{\dot{z}}{\delta_{cs}}(s) \doteq \frac{Z_{\delta_{cs}}\left(\frac{1}{\tau}\right)[\zeta;\omega]}{\left(\frac{1}{\tau}\right)(-Z_w)[\zeta;\omega]}$$

Therefore the open-loop director response to collective can, in general, be expressed as:

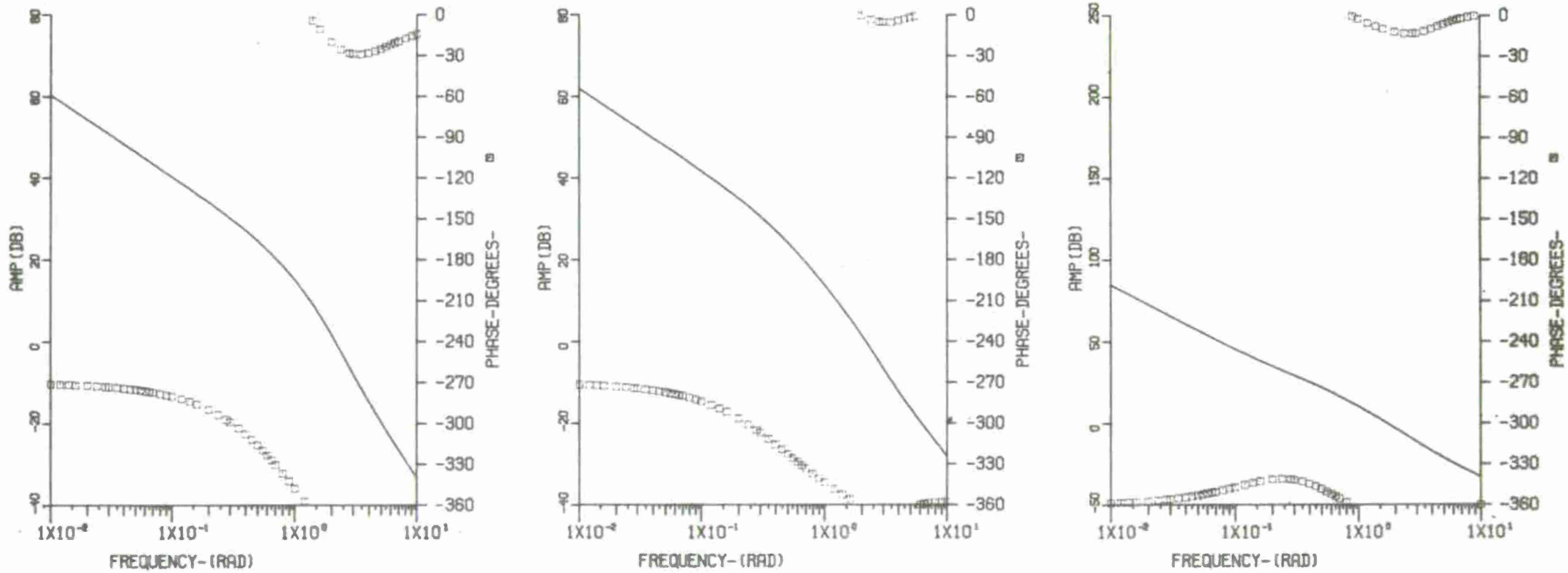
$$\frac{VTAB}{\delta_{cs}}(s) = \frac{K_{\dot{z}} Z_{\delta_{cs}}\left(\frac{K_z}{K_{\dot{z}}}\right)\left(\frac{1}{\tau}\right)[\zeta;\omega]}{(0)(-Z_w)\left(\frac{1}{\tau}\right)\;[\zeta;\omega]}$$

Table 6-7

HBAR/$\delta_\lambda(s)$ TRANSFER FUNCTIONS FOR DVC SYSTEM IN FORM $K\left(\frac{1}{\tau}\right)[\zeta;\omega]$

Flight Condition $(\lambda\,;\,V)$	HBAR/$\delta_\lambda(s)$ ~ volts/deg (±5 volts full scale)
15°; 100 Kt	$\frac{-2.09[0.79;3.58](4.02)}{(0)(0.83)(2.04)[0.88;2.47]}$
50°; 65 Kt	$\frac{-4.18(1.33)[0.7;4.06]}{(0)(0.43)(1.45)[0.86;3.42]}$
90°; 0 Kt	$\frac{-2.44(0.2)(0.89)[0.73;4.11]}{(0)(0)[0.96;0.58][0.90;3.54]}$

A wide frequency band of K/s-like response can be achieved simply by setting the ratio $K_z/K_{\dot{z}}$ equal to $-Z_w$. The results of the preliminary simulator study indicated that a constant-gain collective director might also be suitable for flight; however preliminary flight testing revealed that a collective director optimized for the hover was too sensitive for up-and-away flight. The VTAB gain $K_{\dot{z}}$ was therefore made a linearly increasing function of duct angle



(a) λ = 15^{o} (b) λ = 50^{o} (c) λ = 90^{o}

Figure 6-6 HBAR/$\delta_{\lambda}(s)$ BODE PLOT - DVC SYSTEM

to compensate for the decreasing value of vertical damping (Z_w) of the basic X-22A with increasing duct angle. Other vectored-thrust V/STOL aircraft also exhibit the same reduction in natural height damping through a decelerating transition (e.g., Reference 16) and will undoubtedly require a similar scheme of display augmentation if no artificial height damping is provided. The gain ratio $K_z/K_{\dot{z}}(\lambda)$ was initially set at 0.2 sec^{-1} at $\lambda = 90^{\circ}$ and increased by a factor of ~ 5 over the full range of duct rotation; preliminary flight testing showed that the value of $K_{\dot{z}}$ was too low particularly in the hover. The final hover gain ratio was 0.1 sec^{-1}; similarly this ratio increased by a factor of five over the full range of duct rotation. Based upon simulator results and in-flight verification, the value of K_z was chosen to yield a full scale VTAB deflection for 100 ft of height error. Because of the augmented and decoupled height rate response to collective provided by the DVC system, $K_{\dot{z}}(\lambda)$ was decreased by a factor of five for the DVC evaluations. The final VTAB gains are presented in Table 6-12. The actual VTAB/$\delta_{cs}(s)$ transfer functions for all three longitudinal control systems are presented in Table 6-8; the corresponding Bode diagrams are presented in Figures 6-7 through 6-9.

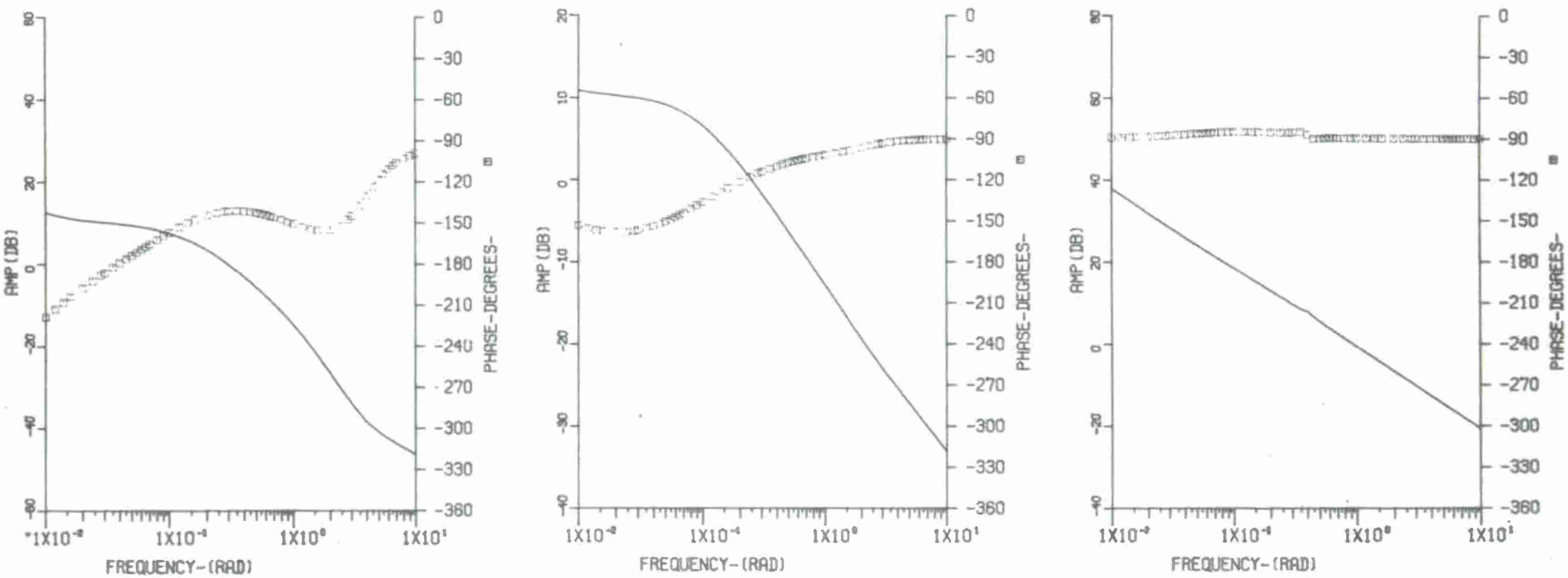
The third director element for the longitudinal control problem, the configuration change director (or ITVIC-Independent Thrust Vector Inclination Command), was developed in the ground simulator and implemented in the form of a light on the left-hand side of the evaluation pilot's instrument panel (Figure 6-1) to give ON-OFF duct rotation commands. As discussed previously, this type of control director corresponds to the nature of the duct angle controller, which is a switch on the collective stick that drives the ducts at a constant 5 deg/sec when activated. The rationale behind the expression for the commanded duct angle ($\lambda_c \sim$ Equation 4-21) is presented in Section 4.4.2. During the deceleration phase of the task, the ITVIC light is ON when λ_c exceeds the actual duct angle by three degrees. When the ducts are rotated to reduce the duct angle error (ϵ_λ) to 0.5 degree, the light is extinguished. This particular value of hysteresis in the ITVIC logic was chosen based upon a preliminary simulator study in which the simulator duct rotation switch was actually used to drive the aircraft's ducts through simulated transitions. The design criteria for the hysteresis circuit were:

- to command a sufficient number of duct rotations so as to minimize the magnitude of the pitch oscillations required for vernier velocity control.
- to minimize the pilot's dwell time on this portion of his display
- to reduce the number of pressure transients in the duct drive hydraulic system.

Table 6-8

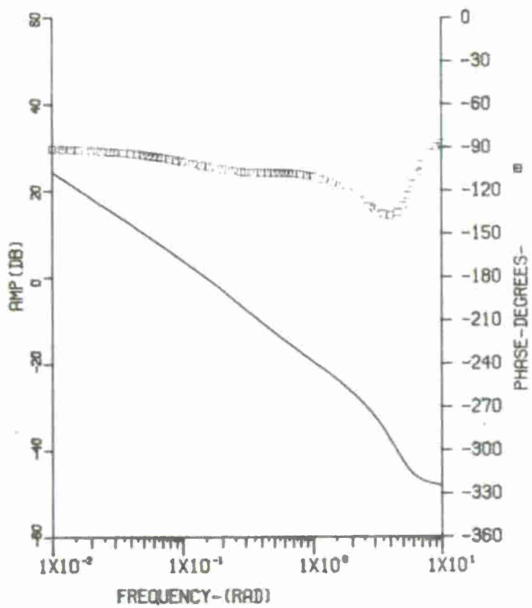
VTAB/δ_{cs}(s) TRANSFER FUNCTIONS IN FORM $K\left(\frac{1}{\tau}\right)[\zeta;\omega]$

Flight Condition	VTAB/$\delta_{cs}(s)$ ~ volt/deg ($\pm$ 5 volts full scale)		
	RATE AUGMENTATION	ATTITUDE AUGMENTATION	DVC
15°; 100 Kt	$\frac{0.052(0.009)(0.44)[0.62;3.80]}{(0)(-0.12)(0.31)(0.93)(2.9)}$	$\frac{0.052(0.44)(0.46)[0.36;5.89]}{(0)(0.23)(0.55)[0.76;4.1]}$	$\frac{-0.026(0.38)(2.17)(8.1)(-12.17)}{(0)(0.83)(2.04)(2.17)}$
50°; 65 Kt	$\frac{0.28(-0.004)(0.22)[0.87;2.03]}{(0)(-0.092)(0.18)[0.94;1.95]}$	$\frac{0.28(0.22)(0.25)[0.7;4.6]}{(0)(0.16)(0.5)[0.7;4.45]}$	$\frac{0.102(0.35)(1.11)[0.57;5.06]}{(0)(0.43)(1.4)[0.86;3.42]}$
90°; 100 Kt	$\frac{0.94(0.1)[0.11;0.41](2.93)}{(0)(0.12)[0.10;0.41](2.94)}$	$\frac{0.94(0.1)(0.17)[0.74;4.29]}{(0)(0.12)(0.17)[0.74;4.29]}$	$\frac{0.34(0.4)(0.49)[0.89;3.45]}{(0)[0.96;0.58][0.9;3.54]}$

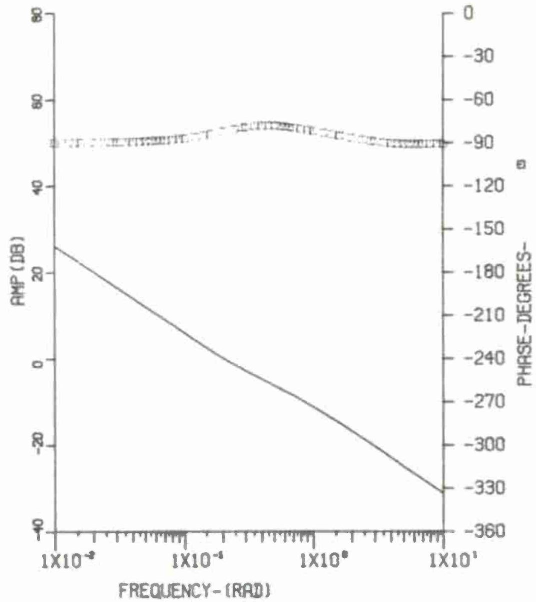


(a) $\lambda = 15^{\circ}$ (b) $\lambda = 50^{\circ}$ (c) $\lambda = 90^{\circ}$

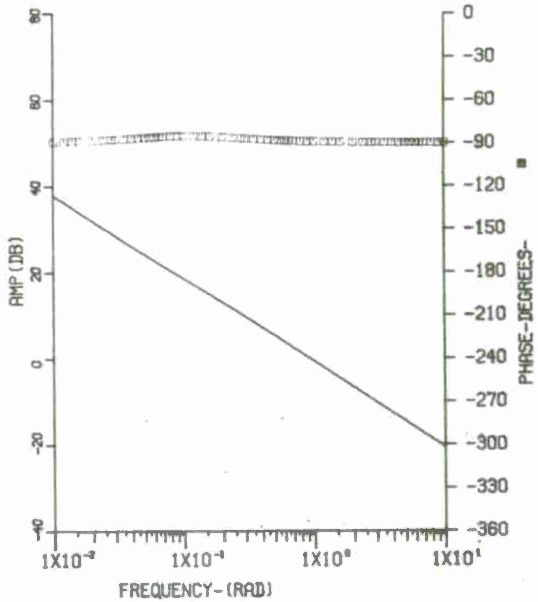
Figure 6-7 VTAB/δ_{cs}(s) BODE PLOT - RATE SYSTEM



(a) $\lambda = 15^0$

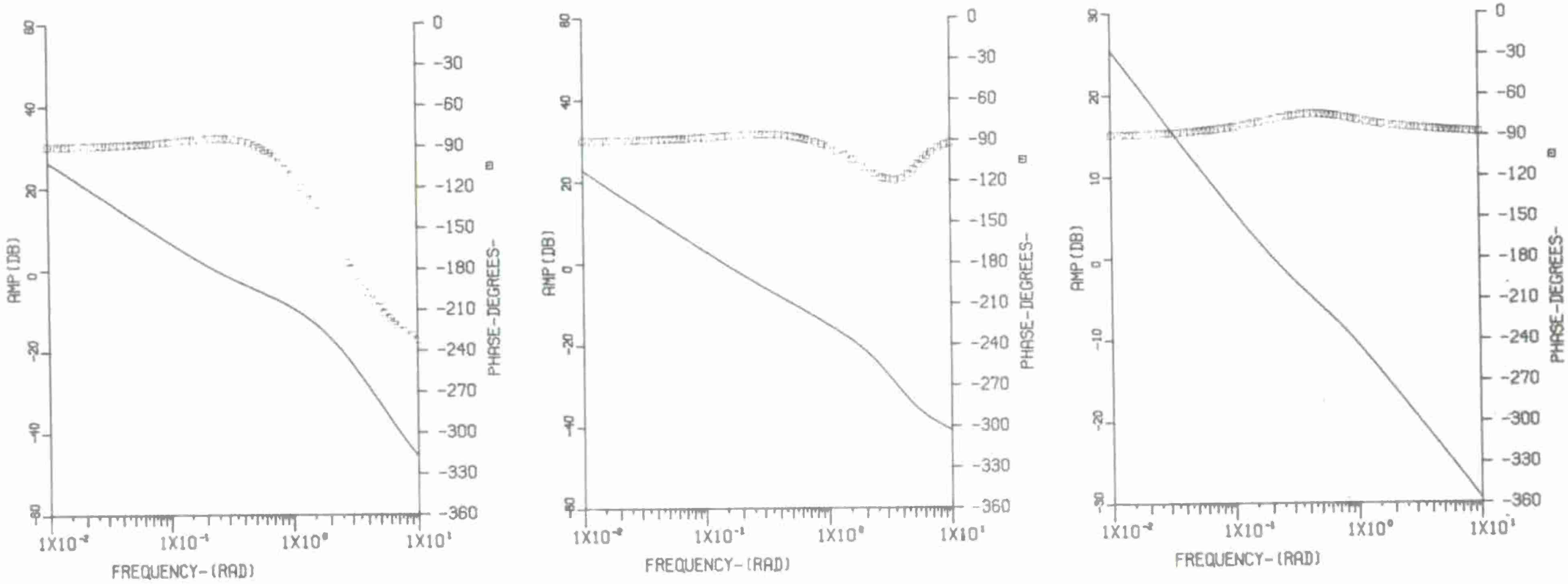


(b) $\lambda = 50^0$



(c) $\lambda = 90^0$

Figure 6-8 VTAB/δ_{CS}(s) BODE PLOT - ATTITUDE SYSTEM



(a) $\lambda = 15^0$ (b) $\lambda = 50^0$ (c) $\lambda = 90^0$

Figure 6-9 VTAB/δ_{cs}(s) BODE PLOT - DVC SYSTEM

6.5.2 Lateral Control Director Design

The same principles which guided the design of the longitudinal directors were also applied to the lateral stick director (VBAR). No director was provided for the rudder pedal either because of an automated directional axis or, in the case of the rate augmentation system, because the pilot simply used the rudders to coordinate his turns during the approach and to establish the desired heading in the hover.

The VBAR control director logic is expressed in a manner analogous to the HBAR expression as:

$$\text{VBAR} = K_{\dot{Y}}\,\epsilon_{\dot{Y}_h} + K_\phi \phi + K_p p = K_{\dot{Y}}\left(\dot{Y}_{h_c} - \hat{\dot{Y}}_h\right) + K_\phi \phi + K_p p \quad \text{(volts)}$$

A heading-referenced lateral velocity error term is used to allow valid director commands for all aircraft headings with respect to the desired approach course. The one exception to the above logic is that, when the heading hold (HH) directional mode is selected, the roll angle feedback to VBAR is washed-out with a 3 second time constant corresponding to the approximate value of Y_v(= -0.3 sec^{-1}) of the basic X-22A. The washout is required for heading hold to avoid standoff errors caused by wing-down approaches and hovering with a crosswind component; the function of the automatic turn coordination (ATC) mode, it will be recalled, is to allow a wings-level approach and hover by continually pointing the aircraft into the relative wind. Again, the body axis angular rate term (p) is used as an approximation to the Euler angular rate term ($\dot{\phi}$) for simplicity of implementation. The director gains K_ϕ and K_p vary as a function of controlled vehicle characteristics but do not vary with flight condition. Their values were selected in order to achieve a K/s -like VBAR/$\delta_{as}(s)$ transfer function in the pilot's frequency region of control for the assumed hover characteristics of the three lateral control systems investigated: attitude command, rate augmentation and rate command/attitude hold systems.

For the attitude augmentation system, the approximate hover transfer functions of interest, assuming perfect heading hold, are:

$$\left.\begin{aligned} \frac{\dot{Y}}{\delta_{as}}(s) &\doteq \frac{g\,L_{\delta_{as}}\left(\frac{1}{\tau_R}\right)}{\left(\frac{1}{\tau_s}\right)\left(\frac{1}{\tau_R}\right)\left[\zeta;\omega\right]} \\ \text{and} \qquad & \\ \frac{\phi}{\delta_{as}}(s) &\doteq \frac{L_{\delta_{as}}\left(\frac{1}{\tau_R}\right)\left(\frac{1}{\tau_s}\right)}{\left(\frac{1}{\tau_s}\right)\left(\frac{1}{\tau_R}\right)\left[\zeta;\omega\right]} \end{aligned}\right\} \quad (6\text{-}4)$$

Recalling from Section IV that the commanded lateral velocity is a linear function of position with the general form $\dot{Y}_c = K_Y Y$, and neglecting the contribution of the washout, the VBAR/$\delta_{as}(s)$ transfer function may be written as:

$$VBAR/\delta_{as}(s) = -K_{\dot{Y}}\left(\frac{s - K_Y}{s}\right)\left(\frac{\dot{Y}}{\delta_{as}}(s)\right) + K_{\dot{\phi}}\left(s + \frac{K_\phi}{K_{\dot{\phi}}}\right)\left(\frac{\phi}{\delta_{as}}(s)\right) \qquad (6\text{-}5)$$

Combining Equations (6-4) with Equation (6-5) and setting $K_Y = -1/\tau_s$ we have:

$$VBAR/\delta_{as}(s) = \frac{K_{\dot{\phi}} L_{\delta_{as}}\left(s + \frac{1}{\tau_R}\right)\left(s + \frac{1}{\tau_s}\right)\left[s^2 + \frac{K_\phi}{K_{\dot{\phi}}}s - g\frac{K_{\dot{Y}}}{K_{\dot{\phi}}}\right]}{s\left(s + \frac{1}{\tau_R}\right)\left(s + \frac{1}{\tau_s}\right)\left(s^2 + 2\zeta\omega s + \omega^2\right)}$$

Therefore in order to create a wide frequency band of K/s-like characteristics, the gain ratios should be set:

$$K_Y = -\frac{1}{\tau_s} \doteq -0.3 \qquad \frac{\text{ft/sec}}{\text{ft}}$$

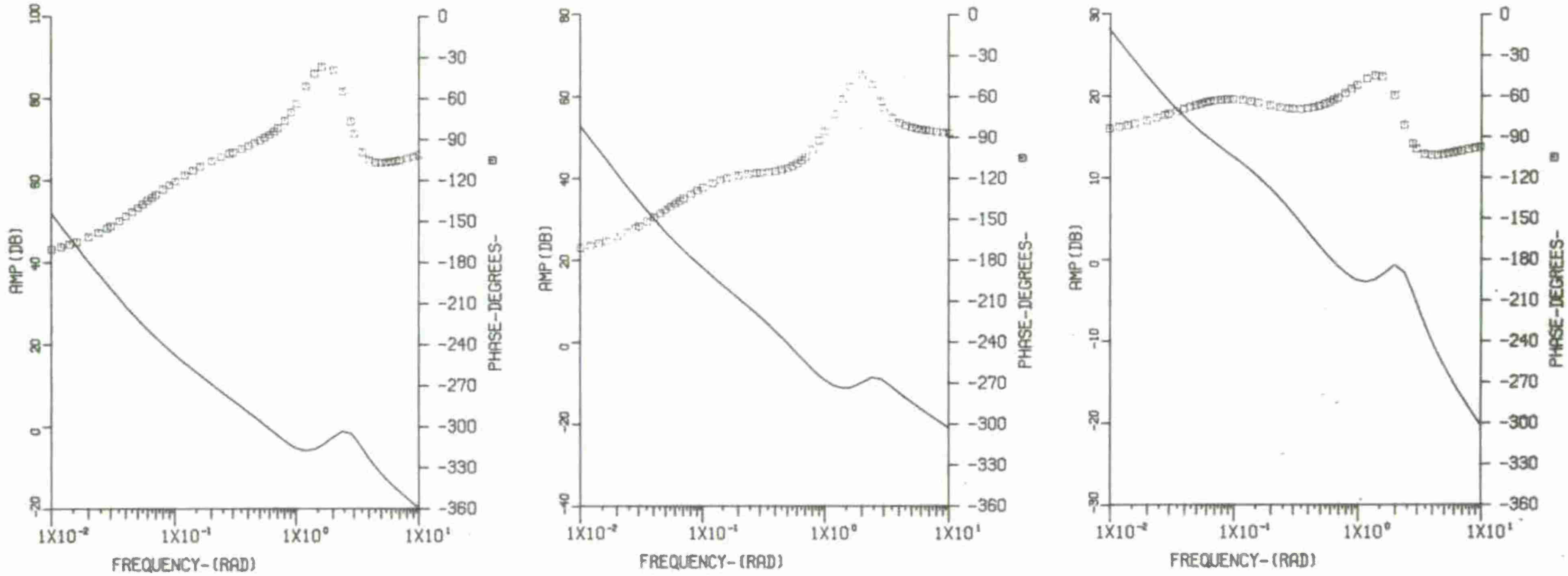
$$\frac{K_{\dot{Y}}}{K_{\dot{\phi}}} = -\frac{\omega^2}{g} = -\frac{(2)^2}{32.2} = -0.124 \qquad \frac{\text{rad/sec}}{\text{ft/sec}}$$

$$\frac{K_\phi}{K_{\dot{\phi}}} \doteq 2\zeta\omega \doteq 2(0.7)(2) = 2.8 \qquad \frac{\text{rad/sec}}{\text{rad}}$$

However, as was discussed in Section IV, the value of K_Y(K_I in Equation 4-13) actually used was K_Y = -.057 ft/sec/ft to be compatible with the command course direction. Hence, the low frequency characteristics of the VBAR director as implemented are not K/s-like in heading hold; these frequencies (ω < 0.3 rad/sec) are, however, well below expected crossover frequencies. The individual values of the remaining gains were determined by the selection of $K_{\dot{Y}}$ in the preliminary simulator study; these values are presented in Table 6-12. The actual VBAR/δ_{as}(s) transfer functions for three flight conditions are presented in Table 6-9; the corresponding Bode diagrams are presented in Figure 6-10.

For the rate augmentation system, the assumed lateral/directional characteristics for perfect turn coordination and a small value of K_Y yielded a generalized VBAR/δ_{as}(s) transfer function of the form:

$$VBAR/\delta_{as}(s) \sim \frac{\left(s^2 + \frac{K_\phi}{K_{\dot{\phi}}} - g\frac{K_{\dot{Y}}}{K_{\dot{\phi}}}\right)\left(s^2 + 2\zeta_\phi\omega_\phi s + \omega_\phi^2\right)}{s\left(s + \frac{1}{\tau_R}\right)\left(s + \frac{1}{\tau_s}\right)\left(s^2 + 2\zeta_d\omega_d s + \omega_d^2\right)}$$



(a) λ = 15°

(b) λ = 50°

(c) λ = 90°

Figure 6-10 VBAR/δ_{as}(s) BODE PLOT - ATTITUDE SYSTEM

Table 6-9

VBAR/$\delta_{as}(s)$ TRANSFER FUNCTIONS FOR ATTITUDE AUGMENTATION IN FORM $K\left(\frac{1}{\tau}\right)\left[\zeta;\omega\right]$

Flight Condition (λ; V; ATC/HH)	VBAR/$\delta_{as}(s)$ ~ volt/in (±5 volts full scale)
15°;100 Kt; ATC	$\dfrac{0.94(0.06)(0.61)[0.49;1.19][0.93;2.44]}{s^2(0.53)[0.76;1.4][0.3;2.64]}$
50°;65 Kt; ATC	$\dfrac{0.9(0.06)[0.62;1.08](1.33)[0.45;2.0]}{s^2(0.49)[0.95;1.63][0.31;2.44]}$
90°;0 Kt; HH	$\dfrac{0.94(0.06)(0.41)[0.84;1.7][0.99;1.98]}{s(0.16)(0.3)(1.7)[0.3;2.2](2.48)}$

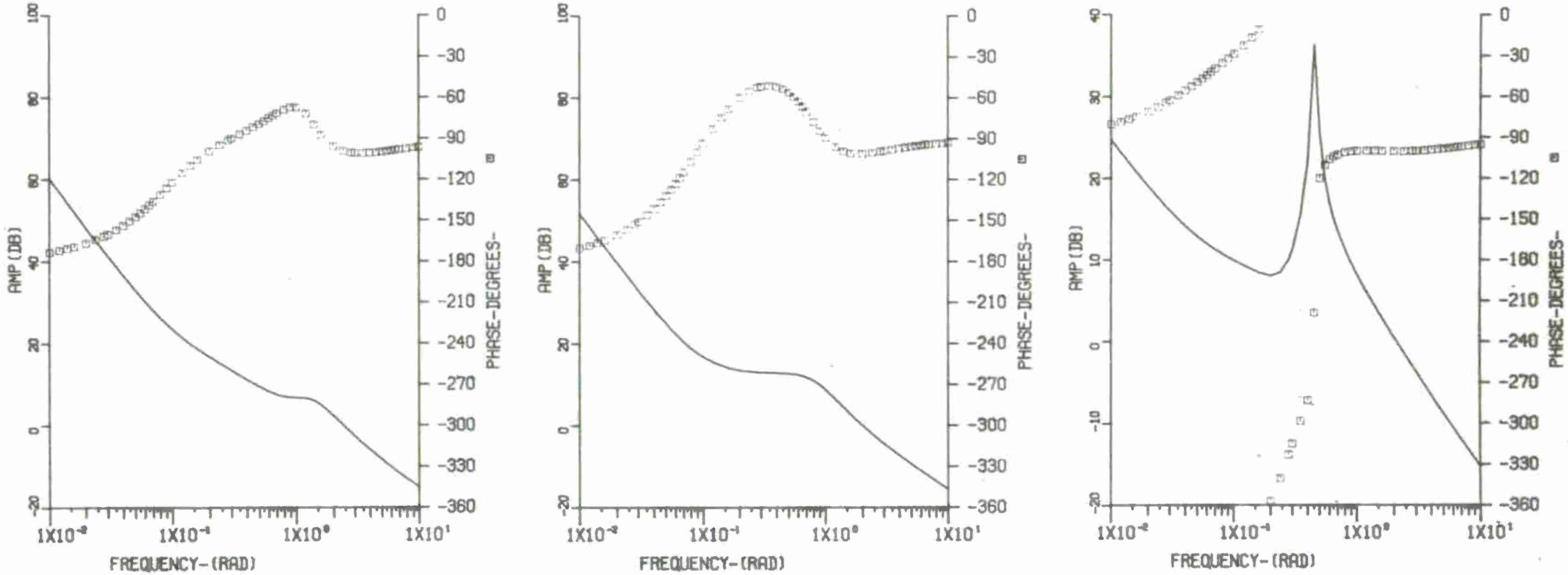
The design goal was therefore to set:

$$\frac{K_\phi}{K_{\dot\phi}} = \frac{1}{\tau_R} + \frac{1}{\tau_s} \doteq 3.0 + 0.3 = 3.3 \quad \frac{\text{rad/sec}}{\text{rad}}$$

and

$$\frac{K_{\dot Y}}{K_{\dot\phi}} = -\frac{\left(\frac{1}{\tau_R}\right)\left(\frac{1}{\tau_s}\right)}{g} = -\frac{(3)(0.3)}{32.2} = -0.028 \quad \frac{\text{rad/sec}}{\text{ft/sec}}$$

The director gains for the rate augmentation system are presented in Table 6-12. The actual VBAR/$\delta_{as}(s)$ transfer function are presented in Table 6-10; the corresponding Bode plots appear as Figure 6-11.



(a) $\lambda = 15^0$ (b) $\lambda = 50^0$ (c) $\lambda = 90^0$

Figure 6-11 VBAR/δ_{as}(s) BODE PLOT - RATE SYSTEM

Table 6-10

VBAR/$\delta_{as}(s)$ TRANSFER FUNCTIONS FOR RATE AUGMENTATION IN FORM $K\left(\frac{1}{\tau}\right)\left[\zeta;\omega\right]$

Flight Condition (λ ; V)	VBAR/$\delta_{as}(s)$ ~ volt/in. (±5 volts full scale)
15°; 100 Kt	$\dfrac{1.71\,[0.9;0.099][0.65;1.08]\,(4.04)}{s^2(0.14)\,[0.42;1.35]\,(3.14)}$
50°; 65 Kt	$\dfrac{1.66\,[0.86;0.095][0.94;1.1]\,(2.99)}{s^2(0.73)\,[0.59;0.8]\,(3.04)}$
90°; 0 Kt	$\dfrac{1.71\,(0.057)\,[0.44;0.28]\,(1.8)\,(3.44)}{s\,(0.3)\,[-0.025;0.45]\,(1.6)\,(2.71)}$

No assumption was made concerning the pilot's use of the rudder pedals in the derivation of the transfer functions presented in Table 6-10; for example, a primary effect of the pilot's efforts in turn coordination during the approach is the effective destabilization of the aircraft's spiral mode caused by the effective increase in weathercock stability. For the $\lambda = 50^\circ$ case, the spiral root would be moved toward zero, thus creating a wider frequency region of K/s-like characteristics. The $\lambda = 90^\circ$ Bode plot demonstrates the effect of a false assumption concerning the location of the complex poles and zeros of the director transfer function during the design phase.

The roll rate command/attitude hold system effectively places an integral plus proportional prefilter term in the attitude command VBAR/$\delta_{as}(s)$ transfer function, i.e.:

$$\frac{VBAR}{\delta_{as}}(s) \sim \left(\frac{s+2}{s}\right)\left[\frac{\left(s+\frac{1}{\tau_R}\right)\left(s-K_Y\right)\left(s^2+\frac{K_\phi}{K_{\dot\phi}}s-g\frac{K_{\dot Y}}{K_{\dot\phi}}\right)}{s\left(s+\frac{1}{\tau_R}\right)\left(s+\frac{1}{\tau_s}\right)(s+2)(s+2)}\right]$$

The design goal for this control system was therefore to create two transfer function zeros, one at 2.0 and the other ($1/T_1$) near zero, i.e., set

$$\frac{K_\phi}{K_{\dot\phi}} \doteq 2 \qquad \frac{\text{rad/sec}}{\text{rad}}$$

and

$$\frac{K_{\dot Y}}{K_{\dot\phi}} = -\frac{2\left(\frac{1}{T_1}\right)}{g} = -\frac{2(0.25)}{32.2} = -0.0155 \qquad \frac{\text{rad/sec}}{\text{ft/sec}}$$

The director gains for the rate command/attitude hold system are presented in Table 6-12. The actual VBAR/$\delta_{as}(s)$ transfer functions are presented in Table 6-11; the corresponding Bode plots are found on Figure 6-12.

Table 6-11

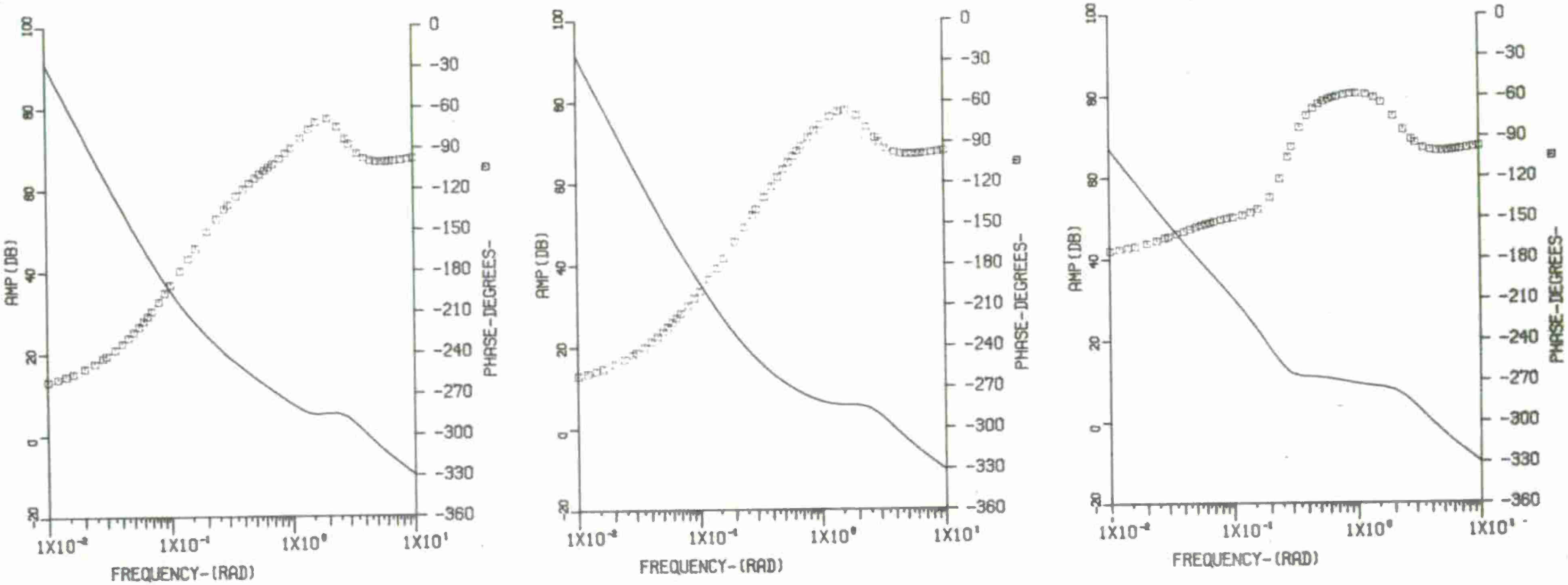
VBAR/$\delta_{as}(s)$ TRANSFER FUNCTIONS FOR ATTITUDE/RATE AUGMENTATION IN FORM $K\left(\frac{1}{\tau}\right)[\zeta;\omega]$

Flight Condition (λ; V; ATC/HH)	VBAR/$\delta_{as}(s)$ ~ volt/in. (±5 volts full scale)
15°; 100 Kt; ATC	$\frac{(2.0)}{(0)} \cdot \frac{3.02(0.1)(0.14)(0.52)[0.55;1.59](2.14)}{(0)(0)(0.52)[0.83;1.49][0.44;2.52]}$
50°; 65 Kt; ATC	$\frac{(2.0)}{(0)} \cdot \frac{2.9(0.083)[0.92;0.36](1.66)[0.87;1.67]}{(0)(0)(0.48)[0.97;1.7][0.48;2.38]}$
90°; 0 Kt; HH	$\frac{(2.0)}{(0)} \cdot \frac{3.02(0.06)[0.4;0.28](1.68)[0.99;2.18]}{(0)(0.16)(0.3)(1.69)[0.52;2.15](2.58)}$

TABLE 6-12

CONTROL DIRECTOR LOGIC

		FULL SCALE SIGNAL				
DIRECTOR ELEMENT	VARIABLE	RATE AUGMENTATION	ATT/RATE AUGMENTATION	ATTITUDE AUGMENTATION	AUTO λ	DECOUPLED VELOCITY CONTROL
HBAR	$\epsilon_{\dot{X}_h}$	$\pm$ 33 (ft/sec)	33	33	33	33
	θ_{WO}	$\pm$ 37 (deg)	75	75	75	--
	q	$\pm$130 (deg/sec)	230	230	230	--
VBAR	$\epsilon_{\dot{Y}_h}$	$\pm$ 42 (ft/sec)	42	42	42	42
	ϕ	$\pm$ 20 (deg)	20	110	110	110
	p	$\pm$ 67 (deg/sec)	38	296	296	296
VTAB	ϵ_Z	$\pm$100 (ft)	100	100	100	100
	$\epsilon_{\dot{Z}}$ (λ = 0)	$\pm$ 50 (ft/sec)	50	50	50	250
	↓	↓	↓	↓	↓	↓
	(λ = 90°)	$\pm$ 10 (ft/sec)	10	10	10	50



(a) λ = 15^0 (b) λ = 50^0 (c) λ = 90^0

Figure 6-12 VBAR/δ_{as}(s) BODE PLOT - ATTITUDE/RATE SYSTEM

6.5.3 Concluding Remarks

The design technique for the control director logic included theoretical analysis, ground simulation, and flight testing. For example, the ground simulator investigations (Appendix III) included the development of the configuration change director light, the selection of the overall director gains, and a verification of the control director design philosophy; preliminary flight testing revealed the requirement for compensating the collective director for the decreasing vertical damping of the basic X-22A and the fact that no obvious need existed for error limiting in the director logic in order to limit the magnitude of the control inputs used in response to a director command. Different director logic was provided for each of the five generic levels of control augmentation discussed in Section V; the major effect of the variations in logic was to cause the pilot to assume more of the aircraft stabilization function as the level of automation decreased. With the exception of the scheduling of the collective director height-rate-error gain with duct angle and the washout of the roll angle feedback to the lateral director in heading hold, no gain scheduling or logic switching as a function of flight condition was utilized. The relatively simple director logic was expected to produce director dynamics which are in general acceptable to the pilot for all flight conditions; the degree to which this design procedure succeeded was high, as will be discussed in Section IX.

Section VII

EVALUATION CONFIGURATIONS

7.1 SYNOPSIS OF SECTION

The purpose of this section is to summarize the variables considered for investigation and to define the combinations of them that made up the configuration matrices for this experiment. Toward this end, the information contained in Sections II through VI of this report is summarized in the next subsection, followed by a subsection defining the configurations that were investigated.

7.2 SUMMARY OF VARIABLES

As was discussed in Section II, the objective of this experiment was to define, through the use of Cooper-Harper pilot ratings and measured performance and workload indices, combinations of representative stability/control augmentation systems and generic levels of displayed information which are satisfactory or adequate for performing VTOL decelerating descending landing approaches on instruments. A review of the pertinent literature in this area was used to reduce the scope of possible investigations to be consistent with a 45-hour flight program; on this basis, the factors selected to be of most importance for variation were (see Table 2-1):

- Control System
  - (1) Type of augmentation (angular rate; angular attitude; translational rates)
  - (2) Degree of automation (none; automatic configuration change; partial or full coupling to guidance data)
- Display Presentation
  - (1) Displayed information (positions; positions plus velocities; control directors)
  - (2) Information integration (separated status and director information; integrated display)
  - (3) Additional information (configuration change director)
- Environmental
  - (1) Magnitude and direction of wind, level of turbulence (only wind direction independently controlled)

These factors constituted the primary independent variables of the experiment. Other factors of importance, such as evaluation task (Section III) and guidance relationships (Section IV), were designed either on the basis of previous work or to provide improved system performance; the X-22A fixed-base ground simulator was used as a tool to verify these designs (Appendix III).

Section V describes in detail the five control systems that were designed for investigation. For readers who skipped that section, a summary of the implementations is given below; the transfer functions are given in Appendix I.

- Rate Augmentation. This control system is mechanized as rate SAS only, with pitch, roll, and yaw rate stabilization approximately equal to the basic X-22A SAS chosen as a representative level. Although the resulting dynamic characteristics through transition are therefore dependent on the X-22A aerodynamics and hence not completely general, these characteristics are representative of this class of V/STOL aircraft, and the results for these configurations therefore provide a suitable base for minimal augmentation complexity. Duct rotation (aircraft configuration change) is manual.

- Attitude Command Augmentation. This system is the baseline configuration chosen to be similar to that used in the NASA-Langley VALT experiments (Reference 5). The directional axis is dual mode, selectable by the pilot; one mode is automatic turn following (zero sideslip) implemented by feeding back lateral velocity and washed-out yaw rate in the directional channel, and the other mode is yaw-rate-command-heading-hold, implemented by closing a heading loop in the directional channel, removing the washout on yaw rate, and using a proportional-plus-integral filter on the rudder commands. Both the pitch and roll axes provide attitude command responses, although the implementations were different. In the pitch channel, the aircraft is highly attitude augmented ($\omega_n \cong 4.0$ rad/sec at hover) to minimize turbulence response and coupling inputs from the collective; the pitch stick commands are then shaped through a second-order pre-filter "model", with feedforward gains on stick input, model pitch rate, and model pitch attitude used to ensure second-order aircraft response. The prefilter characteristics ($\omega_n = 2.0$ rad/sec, $\zeta = 0.7$) were chosen to be consistent with "good" short-term longitudinal response characteristics as determined in an earlier X-22A experiment (Reference 10). In the lateral channel, system limitations precluded a similar implementation, and so attitude augmentation only, of a lower level, was used ($\omega_n \cong 2.0$, $\zeta \cong 0.3$ at hover). Again, duct rotation is manual.

- Pitch Attitude Command/Roll Rate Command. This system is similar to the attitude command system described above except that an integral-plus-proportional prefilter (0.5 second lead) is added to the roll stick input to provide a rate-command-attitude-hold roll response. The purpose of this control configuration was to ascertain if tracking and hover performance would be the same for roll rate command and attitude command. As with the baseline control system, duct rotation is manual.

- Automatic Duct Rotation. This control system represents an increase in complexity from the baseline attitude command system by making the duct rotation automatic instead of manual. The pitch, roll, yaw, and collective stick implementations and response characteristics are identical to those of the attitude command configuration. The automatic rotation is provided by feeding the ITVIC director signal (see Section IV) to the duct rotation system.

- Decoupled Velocity Control. This control system is the most complex investigated, and in fact is only one step away from a fully automatic system. The intent of the design was:

  (1) To provide decoupled responses to collective stick (vertical velocity with respect to the ground) and duct angle (longitudinal velocity with respect to the ground) over the full range of duct angles from forward flight to hover.

  (2) To provide augmented damping and hence improved aircraft responses in vertical and longitudinal velocity.

  (3) To minimize pitch attitude input requirements through the transition.

In order to meet the design goals, the vertical and longitudinal velocity errors as determined by the guidance system were used in feedback loops in the control system in addition to the conventional aircraft quantities. Some degree of decoupling and augmentation was sacrificed in an effort to avoid the necessity of programming all the feedbacks and cross-gearings as a function of duct angle, and in fact in the final design only one programmed cross-gearing (collective to pitch stick) was used.

The major display variable in this experiment was the format on a head-down electronic display which presented integrated horizontal and vertical status and command information of varying generic levels; an additional display selection provided command information separately on an electromechanical ADI. Section VI gives a detailed description of the design of the five levels of display sophistication that were selected for investigation; schematic diagrams of the electronic display (ED) formats are repeated in Figure 7-1 and summarized below.

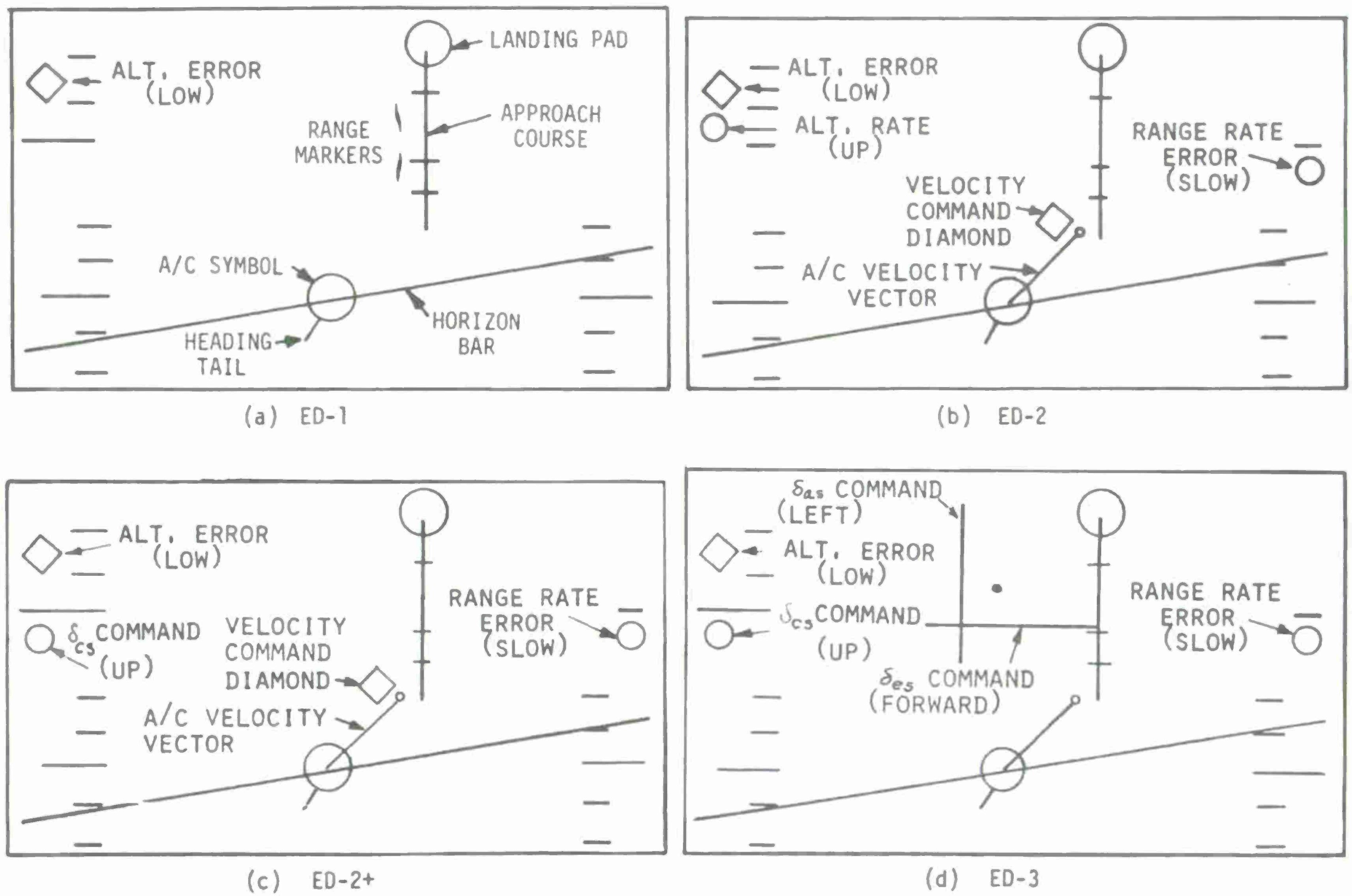


Figure 7-1 ELECTRONIC DISPLAY FORMATS

- <u>ED-1</u>. This display represents ILS (and DME) position information only in an integrated horizontal and vertical format. Aircraft pitch and roll attitudes are shown relative to a fixed aircraft symbol as is typical of an ADI, and yaw heading is shown relative to the approach course by a "tail" on the aircraft symbol. Vertical (glide slope) error is indicated, as is longitudinal distance from the landing pad and lateral distance from the desired course (localizer). The information is displayed in the course-up reference frame (shown in Figure 7-1) when the turn-following directional control mode is selected, and in a heading-up frame when the heading-hold mode is used (see Section IV for a definition of axes systems); for the rate augmentation control system, either display reference frame is available although no changes in directional augmentation are included. The intent of this format was to determine whether position-information only would be adequate with the more complex control systems.

- <u>ED-1/FD</u>. This display represents the effects of separating status and command information on two instruments, and was selected to provide a direct comparison with the NASA VALT results (Reference 5). The electronic display format remains as with ED-1, but three-axis control director information is added to the electromechanical ADI located below the electronic display. The control directors are a longitudinal moment stick command, lateral moment stick command, and collective pitch stick command; they are driven by the same logic used for the ED-3 display to be described below.

- <u>ED-2</u>. This display represents improvements that may be possible if translational rates as well as positions are available, and is the first increase in the hierarchical levels of information discussed in Section VI. All the information on ED-1 is retained, to which is added vertical velocity error information plus actual and commanded horizontal velocities (see Section IV for a description of the commands). The vertical velocity error is shown relative to the same index as the position error, and is in the "fly-from" sense so that positioning the velocity symbol (circle) inside the position symbol (diamond) results in exponential glide slope capture. The horizontal velocity is represented as a vector emanating from the fixed aircraft symbol, and the command as a diamond whose position is determined by the guidance logic; the pilot's task is to control the velocity magnitude and direction to put the tip of the vector in the diamond. Again, the information can be referenced either course-up or heading-up, as with ED-1. In addition, the sensitivity of the horizontal velocity command and status information (cm/ft/sec) may be quadrupled by the pilot in the hover for better hover performance. As is discussed in Section VI, this format is similar to that used in Reference 14; the intent of investigating it was to determine whether the inclusion of velocity status and command

information without control directors would be satisfactory for some control systems.

- ED-2+. This display is identical to the ED-2 format except that the vertical velocity error information is replaced with a collective stick control director. All other characteristics are unchanged. Since the low vertical damping of most VTOL aircraft (including the X-22A) generally results in difficulties controlling altitude (e.g. Reference 16), the intent of this format was to investigate improvements possible by adding a control director for the vertical axis.

- ED-3. This display is similar to the ED-2+ format; the only difference is that the horizontal velocity command diamond is replaced with pitch and roll stick director bars. For the less complex control systems (particularly rate augmentation), information to aid the pilot in performing aircraft stabilization has generally been considered necessary (e.g. References 5, 9); pitch and roll stick directors include this information in their driving logic (see Section VI), and the intent of this display was to determine when this additional information was needed.

An additional display element that was important is the configuration change director (ITVIC: Independent Thrust Vector Inclination Command). The need for and conception of the logic driving this command was discussed in Section IV, and its implementation as a director light was described in Section VI. The duct rotation controller is an ON-OFF switch on the collective stick which drives the ducts at a constant rate (±5 deg/sec) when pushed ON: the ON-OFF ITVIC light is consistent with this controller operation. The light is ON when a commanded duct angle (computed as a function of commanded velocity) exceeds the actual duct angle by 3 degrees; when the ducts are rotated to reduce the duct angle error to 0.5 degree, the light is extinguished. The purpose of this additional display element was to aid the pilot in performing the precise thrust-vector scheduling required to perform the evaluation task (constant deceleration on the glide slope), and the intent of including it was to ascertain if such a director is required for VTOL aircraft.

The control systems and display presentations discussed in the preceding paragraphs form the two primary dimensions of the configuration matrices for which flight evaluations were performed in this experiment to obtain the requisite pilot rating, performance, and workload data. The evaluation configurations are defined in the next subsection.

7.3 EVALUATION CONFIGURATIONS

7.3.1 Primary Configuration Matrix

In order to reduce the effects of environmental factors (wind magnitude and direction, turbulence level) on the pilot rating data obtained in this experiment, the majority of the evaluations were conducted with the wind direction no more than 45 degrees, and usually less than 25 degrees, different than the desired course bearing, and with a headwind component. The

effects of a pure crosswind were investigated separately to some extent, as will be discussed in Section 7.3.2. Wind magnitude and turbulence level, however, varied considerably for these evaluations, a fact which is due to the limited flight time available for evaluation repeats in consistent weather conditions. Approximate values of headwind component, crosswind component, and turbulence level are summarized in Appendix I for each evaluation, and the procedure for obtaining these estimates is given in Appendix VII.

The control-system/display-presentation combinations evaluated when crosswinds were not considered a major influence on the evaluation are shown in Figure 7-2, with the type of display shown on the vertical axis and the type of control system on the horizontal axis. This method of presentation is for convenience only, and should not be interpreted quantitatively. All of these primary evaluations were obtained using the ITVIC director; a brief separate investigation of the lack of this director is summarized in Section 7.3.3. The selection of configurations was based on attempting to:

(1) Define satisfactory combinations for the task.

(2) Demonstrate the hypothesized interaction of Reference 1 for satisfactory and adequate combinations (as control system complexity increases, the required display sophistication decreases).

(3) Provide a proper flying qualities experiment (Cooper-Harper pilot ratings covering a range from approximately 2 to 8).

(4) Provide information relevant to existing VTOL aircraft.

As can be seen from Figure 7-2, all control system were evaluated with the three display formats having the highest level of information sophistication (ED-2, ED-2+, ED-3); this group was expected to encompass the satisafctory combinations, and, in addition, is sufficiently complete to separate out control system or display presentation influences on pilot rating. The lower left hand portion of the figure was not considered useful for evaluation after the preliminary checkout flights, because the paucity of information on the ED-1 display would probably have led to aborted approaches with the control systems requiring manual duct rotation, even with the ITVIC. The two most complex control systems (Auto λ and DVC) were investigated with this format, however, to emphasize interactive effects. Finally, the combination of attitude command (ATT) control system and ED-1/FD display presentation, which corresponds to the NASA VALT configuration (Reference 5), was included both to compare the results and to ascertain the importance of integrated displays; it was not considered relevant for either of these reasons to investigate other configurations using the ED-1/FD display.

It is emphasized that these configurations were also selected to provide information directly relevant to providing an instrument transition capability for existing VTOL aircraft in terms of assessing trade-offs between

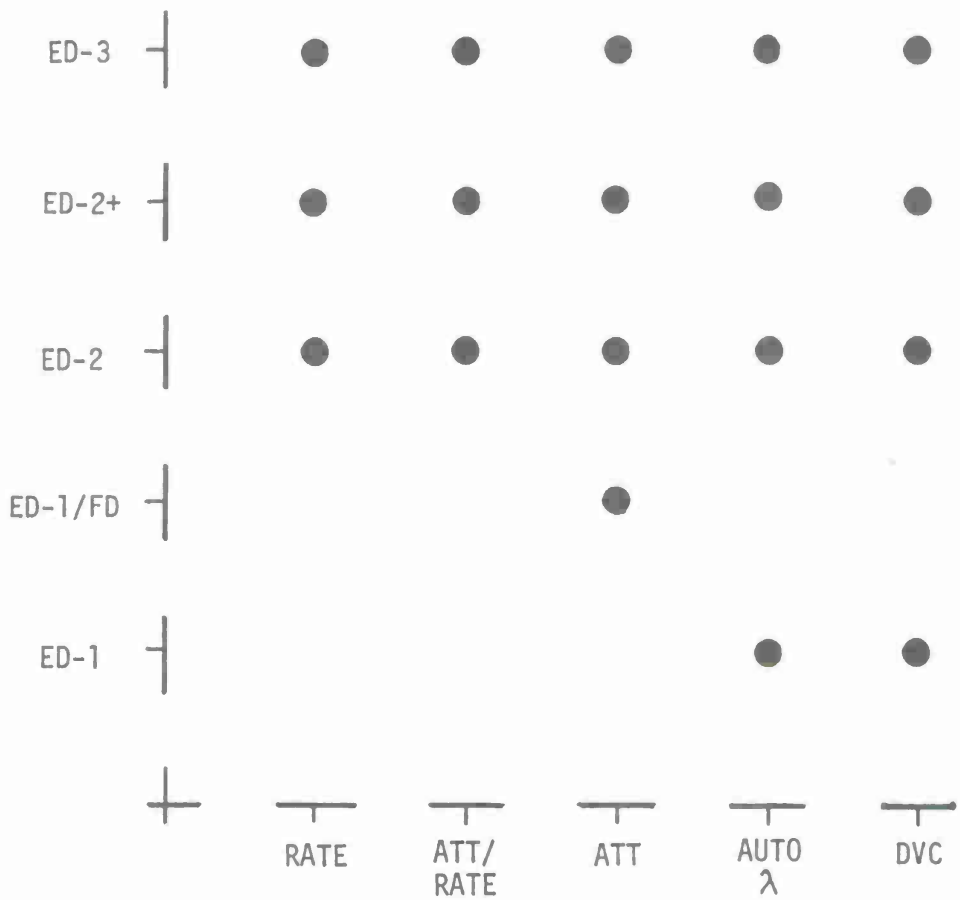


Figure 7-2 PRIMARY EVALUATION CONFIGURATION MATRIX

modifying their current control augmentation systems and acquiring sophisticated displays. For example, the Kestrel uses angular rate damping only (Reference 21) in its stability/control augmentation system, the dynamic characteristics of which are worse (less damping) than those implemented in this experiment. The question then is whether improving these characteristics and adding a control-director display will result in a satisfactory instrument transition capability, or whether a more complex augmentation system is necessary. Similarly, the designer of a new aircraft who is told the display system will be of a given type needs to know what type of control augmentation will be required. The consideration of all five control system types in combination with the three most sophisticated display presentations is intended to provide some guidance in answering these questions.

7.3.2 Crosswind Configurations

A brief investigation of the effects of a pure crosswind was performed in addition to the primary evaluations described above. The major reason for these crosswind configurations was to demonstrate the usefulness of the dual-mode directional system in such conditions, and the effects on pilot rating of not having such a system if wind information is not displayed. Hence, as is shown in Figure 7-3, four of the primary configurations were also evaluated in a pure crosswind of approximately 10 kt; the fifth configuration (RATE: ED-1/FD) was evaluated for comparison with the RATE: ED-3 configuration to determine whether or not any advantages accrued from integrated information in this situation. As with the primary matrix, these configurations all included the ITVIC director.

7.3.3 No ITVIC Configurations

It was originally intended to evaluate many of the configurations using manual duct rotation (the rate augmentation, attitude/rate command, and attitude command control systems) both with and without the ITVIC director in order to ascertain its efficacy. As will be discussed in Section IX, only two repeats from the primary matrix were necessary in this regard. The two configurations evaluated without the ITVIC director were the ED-3 and ED-2 displays in combination with the attitude command control system.

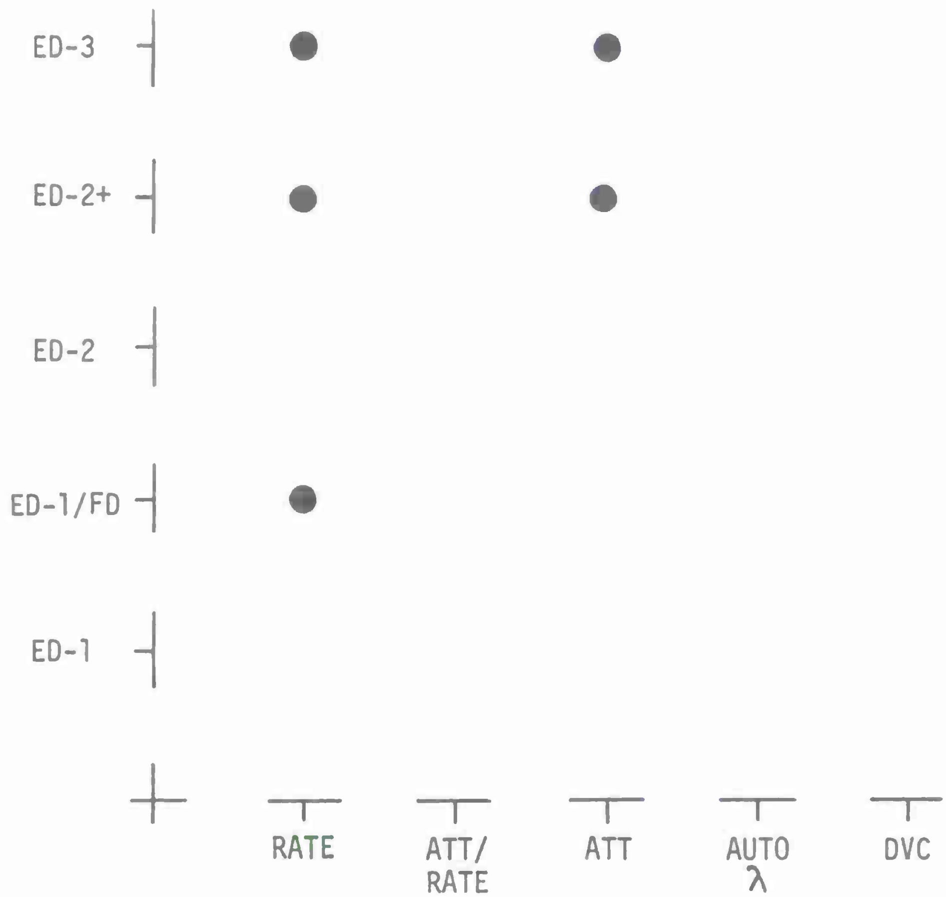


Figure 7-3 CROSSWIND EVALUATION CONFIGURATION MATRIX

Section VIII

CONDUCT OF THE EXPERIMENT

8.1 SYNOPSIS OF SECTION

The purpose of this section is to outline the procedures that were used in conducting this flight experiment. The following subsections outline the equipment used, set-up procedures, simulation situation, evaluation procedure, and the types of data obtained in the experiment.

8.2 EQUIPMENT

8.2.1 X-22A Variable Stability V/STOL Aircraft

The United States Navy X-22A V/STOL variable stability aircraft was used as the in-flight simulator for this experiment (Figure 8-1). Briefly, the X-22A is a four-ducted-propeller V/STOL aircraft with the capability of full transition between hover and forward flight. The four ducts are interconnected and can be rotated to change the duct angle (λ) and therefore the direction of the thrust vector to achieve the desired operating flight condition defined by a particular speed and duct angle combination. The thrust magnitude is determined by a collective pitch lever, very similar to a helicopter. Normal aircraft-type pitch, roll and yaw controls in the cockpit provide the desired control moments by differentially positioning the appropriate controls in each duct (propeller pitch and/or elevon deflection). A mechanical mixer directs and proportions the pilot's commands to the appropriate propellers and elevons as a function of the duct angle.

The X-22A incorporates a Calspan-designed four-axis (pitch, roll, yaw, thrust) response-feedback variable stability system (VSS) plus a 96-amplifier analog computer designed and fabricated by Calspan for this flight experiment. The mechanization of the control augmentation systems discussed in Section V is performed by the VSS in conjunction with aspects implemented on the analog computer (e.g. command pre-filtering); the analog computer also provides the guidance data smoothing, command generation, and control director logic. The evaluation pilot's control inputs (from the left hand seat in this aircraft), in the form of electrical signals, are summed through the analog computer and VSS with the appropriate signals proportional to the aircraft motions to operate the right hand flight controls through electrohydraulic servos. The system operator, who also serves as the safety pilot, occupies the right hand seat, and operates the aircraft through the primary flight control system when the VSS is disengaged. All of the VSS input and response-feedback gain controls are located beside the safety pilot; ten potentiometers for the analog computer are located next to the evaluation pilot.

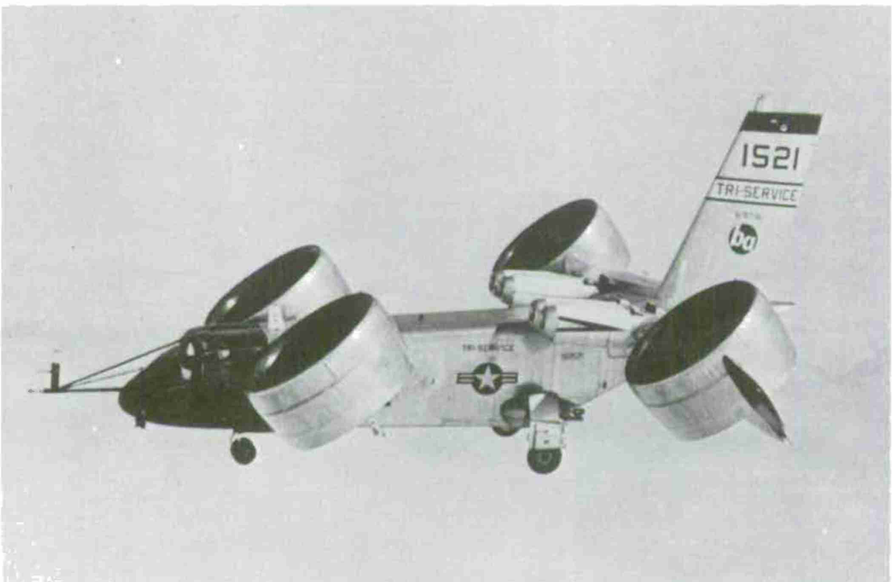


Figure 8-1 X-22A VARIABLE STABILITY V/STOL AIRCRAFT

Control feel to the evaluation pilot's stick and rudder pedals is provided by electrically controlled hydraulic feel servos which provide opposing forces proportional to the stick or rudder deflections: in effect, a simple linear spring feel system. An adjustable friction level is provided for the collective stick. Note that the evaluation pilot can not feel the X-22A control motions produced by the variable stability system.

To provide a variable display capability, a Calspan-designed-and-fabricated analog symbol generator in conjunction with a 5" Kaiser CRT were added to the aircraft (References 25, 44). The programmable symbol generator is capable of producing as many as 32 different calligraphic symbols, and combines the simplicity and ease of programming available in an analog computer with an in-flight flexibility exceeding that of more complex digital devices. Ten combinations of the thirty-two output channels can be individually blanked through the use of switches in the cockpit located next to the evaluation pilot; additionally, a display mode switch selects different inputs to the symbols to provide either an approach-course-up or heading-up reference for the display format. These capabilities are very important for in-flight research experiments, as different display presentations may be evaluated during flight without landing and reprogramming the symbol generator. The evaluation pilot's instrument panel incorporating the CRT is shown in Figure 8-2.

A more complete description of the X-22A system is contained in Reference 45 and summarized in Appendix VIII, which also contains diagrams of the analog computer programs.

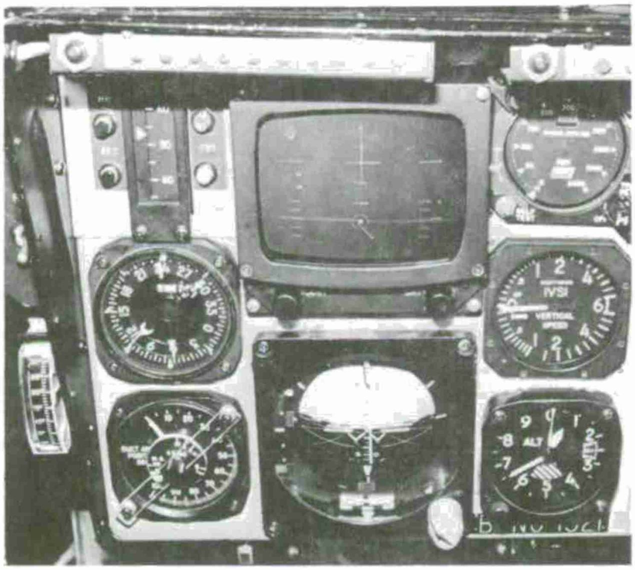
8.2.2 AN/SPN-42T1 Tracking Radar

For this experiment, the raw X, Y, Z position data were provided by an AN/SPN-42T1 precision tracking radar manufactured by the Bell Aerospace Company (Reference 46). As used in this application, elevation, azimuth, and range radar information was resolved into X, Y, Z components relative to one of five selectable approach course directions; these components were telemetered to the aircraft using the scalings discussed in Section IV of this report. A differential resolver in the aircraft was set at the selected course bearing to provide aircraft heading information relative to the appropriate direction (see Section IV). As has been discussed, all processing of the X, Y, Z data were performed on-board the aircraft by the analog computer, and hence the relationships are essentially independent of the actual AN/SPN-42T1 equipment.

The operation of the radar system was as follows. Prior to LOCK-ON of the target (the X-22A), the system is in a "search" mode. To achieve LOCK-ON, the aircraft must be flown through a capture window defined by:

- azimuth angle within ± 12-1/2 degrees of one of the inner three selectable course directions

- altitude within ± 500 feet of the desired altitude, usually set at the initial approach altitude (1700 ft AGL)



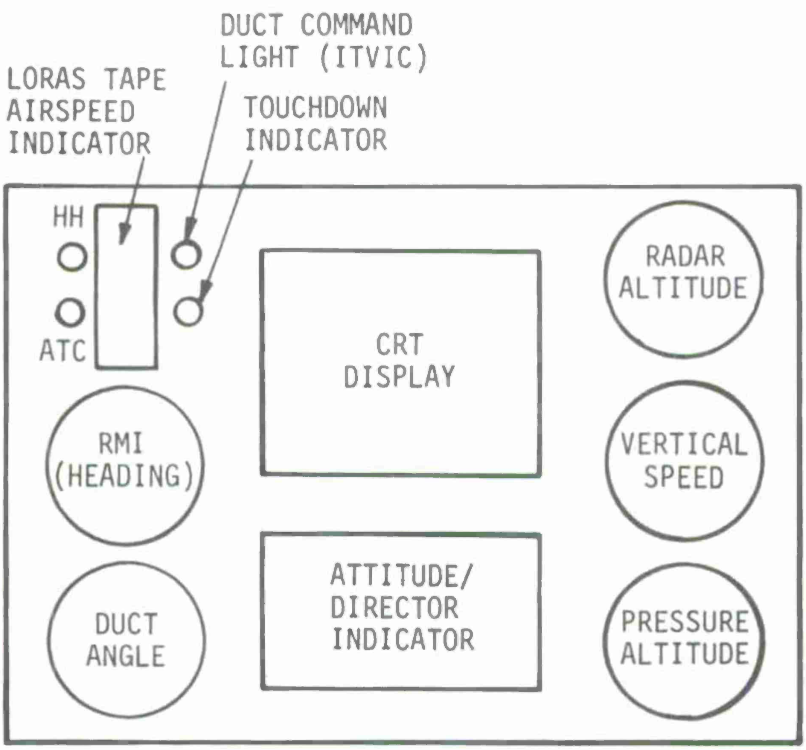


Figure 8-2 EVALUATION PILOT INSTRUMENT PANEL

- range within ± 1/2 mile of estimated range

When the aircraft meets the capture conditions, LOCK-ON is achieved and telemetered data is sent to the aircraft. As was discussed in Section IV, digital scaling limitations resulted in a saturated X_e signal until within 17,480 feet of the hover spot. The sensitivities of the data as displayed to the pilot are discussed in Section VI.

8.2.3 Data Acquisition System

Both experimental and flight safety data were telemetered to and monitored by the Digital Data Acquisition and Monitoring System developed expressly for the X-22A by Calspan and housed in a mobile van. Since the complexity of the X-22A makes it impossible for the pilot to monitor all the important flight safety parameters, it is essential to have ground monitoring of the flight safety variables. The flight safety variables were monitored on chart recorders and by a digital mini-computer in the van. In addition, a continuous recording of all telemetered data, including radar position data and the guidance relationships performed in the analog computer, was obtained on the "bit-stream" recorder for later analysis and processing. During the program, good telemetry coverage was achieved at ranges between the van and the X-22A of up to twenty miles. The details of the Digital Data Acquisition System are covered more fully in Appendix VIII.

8.3 CONFIGURATION SET-UP PROCEDURE

Prior to the initiation of the evaluation approaches for each configuration, the characteristics of the control-system/display-presentation combination to be investigated were set-up in flight by both pilots before engagement of the variable stability system. The set-up functions to be performed by each pilot were listed on a card for each configuration, and are summarized below.

Safety Pilot

- Set all variable stability system gains in thrust, pitch, roll, yaw.
- Select via two-position switch whether guidance information would be used in the control system feedback loops (the DVC system only) or not (the rate, attitude/rate, attitude, and automatic λ systems).

Evaluation Pilot

- Set selected approach course on differential resolver (ψ_A).
- Select via two-position switch whether manual or automatic duct rotation would occur.

- Select via two-position switch whether or not the ITVIC light was operative.

- Select via two-position switch whether or not the needles on the electromechanical ADI were driven by the control director logic (for the ED-1/FD display only) or inactive (displays ED-1, ED-2, ED-2+, ED-3).

- Select electronic display (ED) format to be evaluated by setting the 10 blanking switches for the symbol generator as instructed.

- Set 10 potentiometers from the analog computer as instructed for additional display changes (e.g. the different control director gains for each control system) plus some control system functions (e.g. whether or not the ATC-HH directional augmentation was active).

The evaluation pilot was also provided with a "push-push" switch on the collective stick to select the desired directional mode (turn-following or heading-hold) when this augmentation was functioning (all control systems except rate augmentation); colored lights on the instrument panel indicated which mode was selected. As has been noted previously, this switch also selected the reference frame for the electronic display format (either course-up or heading-up), with the course-up formats given when the turn-following mode was engaged; the selection of the reference frame was functional even when the dual-mode directional system was not used (i.e. the rate augmentation control system).

As part of the set-up, the evaluation pilot's card explicitly provided him with the following information about the configuration to be evaluated:

- Which electronic display format (ED-1, ED-2, ED-2+; ED-3) he would have.

- Whether or not the ITVIC light was operative.

- Whether or not the needles on the electromechanical ADI gave control director information.

- Whether duct rotation was manual or automatic.

- Whether or not the ATC-HH directional control system was operative.

To some extent, providing this information is at variance with the usual procedure in flying qualities experiments of giving the evaluation pilot no information regarding the configuration to be evaluated. In an experiment which varies displayed information as well as aircraft response characteristics, however, the pilot must understand what the displays contain so that he can accomplish the task; the first three items listed above relate to this require-

ment. Although the pilot was not told explicitly which control system he would be evaluating, it was considered necessary to tell him if he was required to perform the configuration changes manually so that he would be prepared to do so, and also to warn him if the ATC-HH mode was not operative so that he would not think a failure had occurred. Since the types of control systems investigated provided obvious differences in response characteristics, the evaluation pilot could tell immediately upon VSS engagement which system he had, but in general he did not know whether or not the combination had been previously evaluated, nor was he able to remember any previous pilot ratings given to it (partially as a result of fairly long "down" times during the course of the experiment caused by weather restrictions and an unexpected frequency of AN/SPN-42T1 system failures).

8.4 SIMULATION SITUATION

To obtain valid flying qualities data in the form of pilot ratings and comments, careful attention must be given to defining, for the evaluation pilot, the mission which the aircraft/pilot combination will perform and the conditions in which it will be performed. For the current experiment, the simulated aircraft was defined as an all-weather VTOL transport (Class II of MIL-F-83300, Reference 4) performing terminal area operations; the aircraft was considered a two-pilot operation to the extent that no allowance was made for typical additional duties, e.g., communications. Additional factors such as passenger comfort were not considered by the pilot in making his evaluation.

8.5 EVALUATION TASK

Although the mission generally involves many elements, an evaluation of the suitability of the vehicle for the mission can be accomplished by having the evaluation pilot perform a series of maneuvers representative of those tasks anticipated in the mission. With the general conditions defined as above, the specific tasks to be accomplished for each evaluation were defined as two simulated-IFR ("hooded") approaches from 100 Kt to the hover, employing a decelerating descending transition. The elements of the approach profile were discussed in Section III of this report, and are summarized below and in Figure 8-3:

- level flight localizer acquisition (1700 ft AGL, 100 Kt)
- constant speed glide slope acquisition (7.5 degrees) at approximately 13,000 ft range
- constant deceleration (.05g) on the glide slope, commencing at a range dependent on headwind (zero-wind range approximately 8000 ft)
- flare to level final approach commencing at approximately 800 ft range, final altitude 100 ft, deceleration continuing to hover
- hover at 100 ft above simulated pad, vertical airwork as desired.

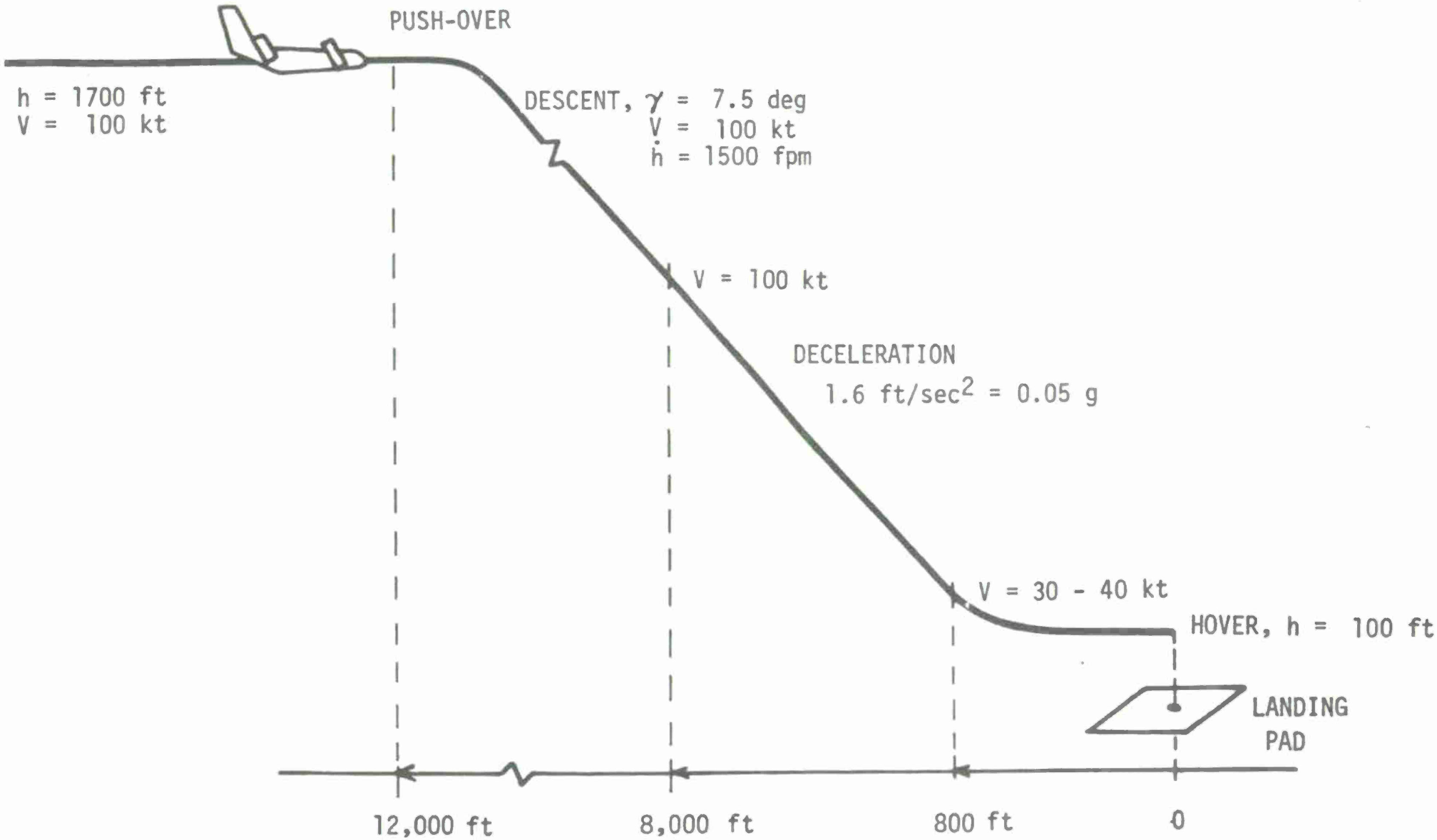


Figure 8-3 EVALUATION TASK

An actual vertical landing was not required but was permissible as an option to the pilot; in general, operational constraints precluded carrying the vertical airwork through to touchdown, although some completely hooded vertical landings were made during the program. The pilot ratings did not, therefore, include the influence of actually landing, but the pilot was asked to extrapolate his hover performance to the instrument landing; it was feasible for the pilot to carry out such an extrapolation in this experiment, because the vertical landing procedure in the X-22A is to set up a constant rate of descent at approximately 20 feet AGL and continue it through the ground effect to touchdown.

8.6 EVALUATION PROCEDURE

The evaluation procedure was as follows. Upon completion of the set-up procedures discussed in Section 8.4, the evaluation pilot "went under the hood", and the safety pilot engaged the VSS and gave control of the aircraft to the evaluation pilot at 1700 ft AGL, heading for the radar capture window. With the exception of the decoupled velocity control (DVC) system, it was not necessary to have radar LOCK-ON for VSS engagement; for the DVC system, however, the use of vertical guidance information in the control system feedbacks did necessitate LOCK-ON prior to VSS engagement. When radar LOCK-ON occurred, the evaluation pilot waited approximately 10 seconds for the complementary filter start-up transients to settle out, and then performed the approach profile described above. At the conclusion of the first hover, the VSS was disengaged and the safety pilot took the airplane back out to the initiation point; the evaluation pilot then performed a second instrument approach in the same fashion. The instrument hover at the end of the second approach was used for the vertical airwork and landing if desired. At the conclusion of the second hover, the VSS was again disengaged, and the safety pilot flew the aircraft outbound to set up the next configuration while the evaluation pilot tape-recorded comments with reference to a detailed comment card and assigned a Cooper-Harper pilot rating (Figure 8-4) and turbulence effect rating (Figure 8-5) to the configuration.

The pilot comment card is given below. It is important to note that the purpose of this card is to aid both the pilot in performing his evaluation and the analyst in determining the major reasons for the rating; as such, the pilot comments obtained in a systematic fashion immediately after the flying of the configuration are valuable data in themselves (see Appendix V).

A. General Comments
   - Aircraft response, displays, winds, pilot?

B. Specific Comments
   1. Approach Performance
      (a) Localizer and glide slope interception
      (b) Localizer and glide slope tracking
         - Deceleration profile reasonable?
      (c) Precision hover
         - Display?
         - Performance ?
         - Could you land?

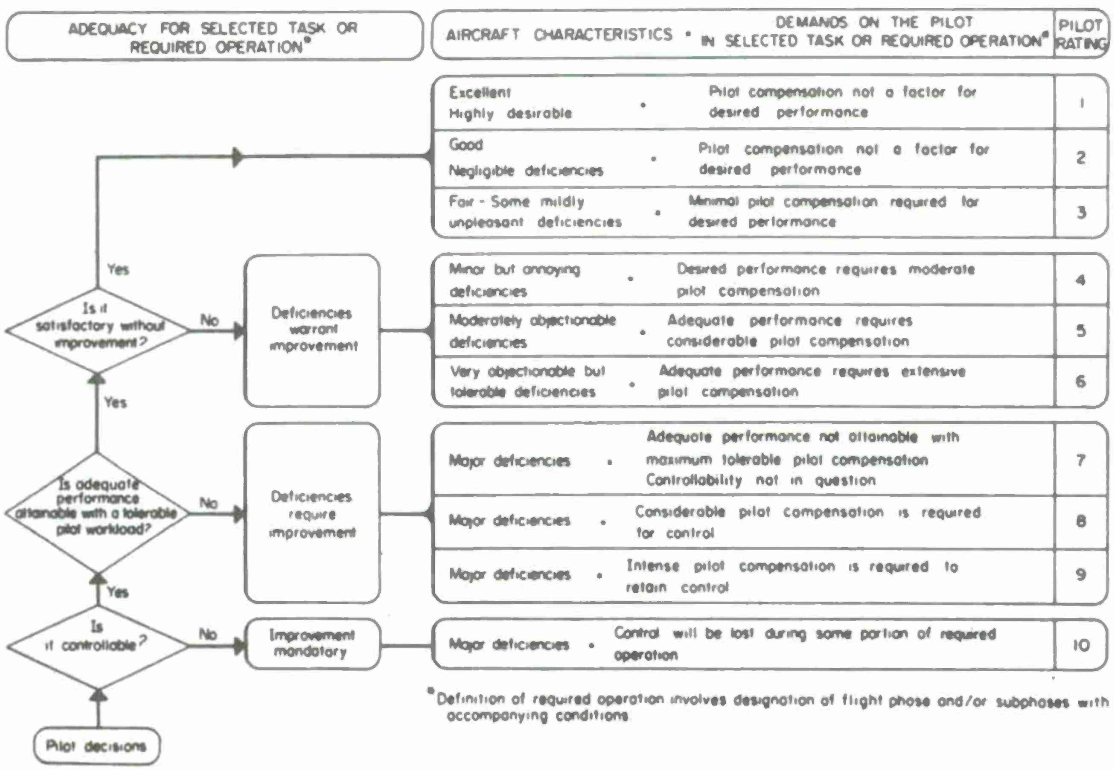


Figure 8-4 COOPER-HARPER PILOT RATING SCALE

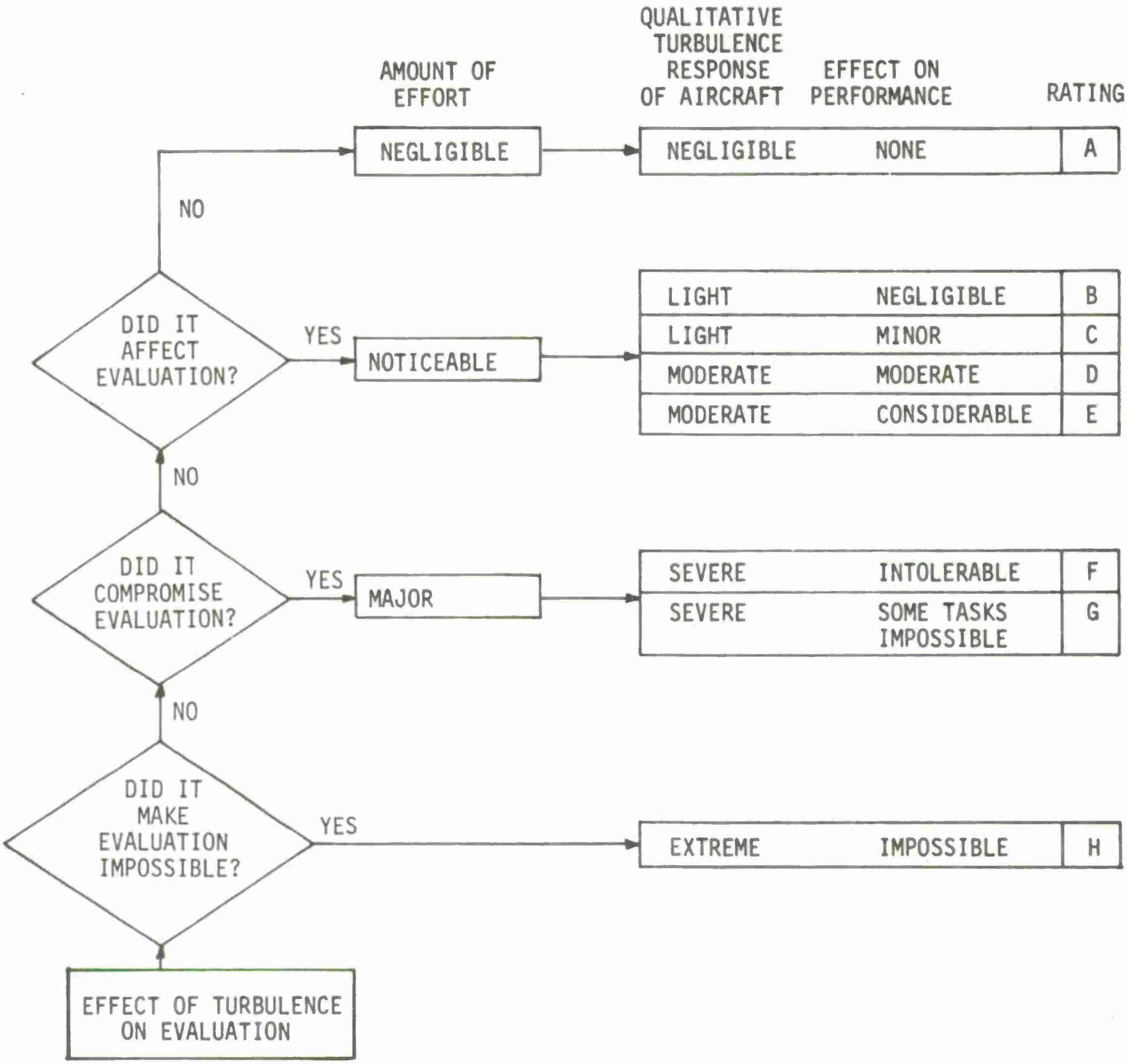


Figure 8-5 TURBULENCE EFFECT RATING SCALE

2. Aircraft Response

   (a) Longitudinal and lateral stick coupling with speed?
   (b) Collective/Throttle
       - Technique?
       - Coupling?
   (c) Rudder Pedals
       - Coupling?

3. Display

   (a) ED and ITVIC (when applicable)
       - Sensitivity?
       - Coordinated with control motions?
   (b) ADI
       - Was it used? When?
   (c) Flight director (when applicable)
       - Any problems?
   (d) Scan pattern
       - Any problems?
       - Peripheral instruments OK?

C. Summary Comments

1. Pilot Rating
   - Identify factors most influencing the rating
2. Turbulence effect rating.
3. Any simulation deficiencies?

Two salient points in the evaluation procedure as described bear consideration:

1. To apply the Cooper-Harper rating scale to the situation in which both displays and control systems are changing, careful definition of the descriptive phrases in the context of the experiment is required. "Controllability", for example, becomes confusing if the aircraft exhibits good response characteristics but the display presents insufficient data to determine the effects on task performance of the responses generated. As interpreted by the evaluation pilot in this experiment, a configuration with a "good" control system (e.g. Auto λ) but a "bad" display (e.g. ED-1) did not exhibit controllability problems even if the displayed information was insufficient to perform one aspect of the task safely (e.g. level-off): a situation of this type was considered not to have adequate performance attainable with a tolerable pilot workload but controllability not in question (PR = 7).

2. The turbulence effect rating is not a quantitative indication of the turbulence level encountered. The pilot rating properly includes the pilot's weighting of the aircraft/display/pilot system in a turbulence environment, and the purpose of the turbulence effect rating is primarily to provide a qualitative indication to the analyst of how much turbulence inputs affected the pilot's ability to judge the aircraft. To this end, the turbulence effect rating scale shown in Figure 8-5 represents a modification of those scales used in previous X-22A programs (References 10, 11) to emphasize more clearly the intended use of these ratings.

8.7 DATA ACQUIRED

The data acquired from this experiment falls into the following categories:

1. Pilot Ratings and Comments
2. Control Usage and Tracking Performance
3. Wind and Turbulence
4. Aircraft Response

Data on aircraft responses were required to estimate the basic X-22A stability and control derivatives, from which the dynamic characteristics presented in this report were computed; details of the identification procedures are contained in Appendix IV. The estimation of ambient winds and turbulence levels is required to interpret both the pilot comment data and the performance/workload indices; this estimation procedure is discussed in Appendix VII. Section IX describes the experimental results in terms of pilot comments and ratings, and Section X discusses these results on the basis of statistical measures of workload and performance.

8.8 EVALUATION SUMMARY

Because of the relatively limited flight time available for evaluations in this program, only one evaluation pilot was used. He is a Calspan Research Pilot with extensive experience as an evaluation pilot in flying qualities investigations, including both previous X-22A research experiments. His flight experience of 4500 hours includes over 500 hours in helicopters, and he is qualified in the X-22A aircraft.

A total of 44.5 hours was flown in this research program, of which 20.4 hours were devoted to evaluation flights; the remaining hours were devoted to calibration and checkout flights plus a few flights aborted because of AN/SPN-42T1 malfunctions. A total of 38 evaluations of 21 control-display configurations was obtained in the program.

Section IX

FLYING QUALITIES RESULTS

9.1 SYNOPSIS OF SECTION

The purpose of this section is to present and interpret the pilot rating data obtained in this experiment. Accordingly, the first subsection discusses the data in terms of pilot commentary (Appendix V), while the second subsection presents a simple interpretation in terms of closed-loop control/display system performance assuming simple pilot loop closures. The pilot rating data is summarized in Appendix I and the comments in Appendix V; frequency responses are given in Appendix II.

9.2 PILOT RATING RESULTS

9.2.1 Primary Configuration Matrix

For convenience in discussing individual configurations, the following abbreviations, consistent with previous sections, and configuration identifier scheme will be used in this section:

Control Systems:

- Rate Augmentation ⇒ RATE
- Pitch Attitude Command/Roll Rate Command ⇒ ATT/RATE
- Attitude Command ⇒ ATT
- Automatic Duct Rotation ⇒ AUTO
- Decoupled Velocity Control ⇒ DVC

Displays:

- Position ⇒ ED1
- Position Plus Separate Directors ⇒ ED1/FD
- Velocity ⇒ ED2
- Velocity Plus Collective Director ⇒ ED2+
- Control Directors = ED3

Configuration Identifier:

- Control System:Display -- e.g. ATT/RATE:ED2+

Pilot comments for a configuration will be identified by flight number (e.g. F-128) for reference to Appendix V.

The pilot rating data for the primary configuration matrix are shown in Figure 9-1 on a "plot" of display sophistication versus control complexity. This means of presenting the data is chosen to facilitate comparison of trends with the AGARD graph in Figure 1-1; it is emphasized that the axes are ordinal rather than interval, and that the approximate iso-rating lines refer only to the data specifically on the figure as a device to emphasize the interactive effects. The data on this figure represent evaluations performed when crosswinds were not considered a major influence on the evaluation - the repeat evaluations chosen to emphasize the important effects of crosswinds will be discussed separately. As was discussed in Section VII, the ITVIC director was used for all these configurations.

Consider initially those configurations for which the pilot rating indicates satisfactory system performance (PR$\leq$ 3.5). In a general sense, the most apparent result is the demonstration of the hypothesized interaction between control complexity and display sophistication: as the level of augmentation and/or automation increases, the required display presentation decreases from full integrated control director information to velocity (and velocity command) information both vertically and horizontally. This trade-off can be seen in the pilot comment data for the three configurations indicated just inside the PR $\leq$ 3-1/2 iso-rating line on Figure 9-1: ATT/RATE: ED3, ATT:ED2+, and AUTO:ED2. Recalling that ED3 has pitch and roll stick directors while ED2+ does not, and that ED2+ has a collective stick director while ED2 does not, as well as that ATT/RATE has roll rate command while ATT has roll attitude command, and that both of these systems require manual duct rotation while AUTO does not, the pilot comments regarding localizer tracking and collective stick control are of interest:

ATT/RATE:ED3 -- "Some problem overbanking the aircraft, but that disipates when I'm tracking the vertical bar closely. Collective is just a matter of following the bouncing ball, no problem" (F-142)

ATT:ED2+ -- "Both localizer and glide slope really very easy, good precision control and I don't get very far off. Collective control very good, simply follow the commands and very seldom overshoot or undershoot." (F-131)

AUTO:ED2 -- "Localizer tracking OK, I liked the localizer guidance. Glide slope tracking is a lot easier with automatic duct rotation... and I didn't undershoot the final altitude as I have before with this display." (F-123) "Tend to lead the collective a little bit." (F-133)

These configurations all received a "satisfactory without improvement" rating of 3, but, as is clear from the comments, for different reasons. Using the ATT:ED2+ configuration as a base, a degradation in the control system roll

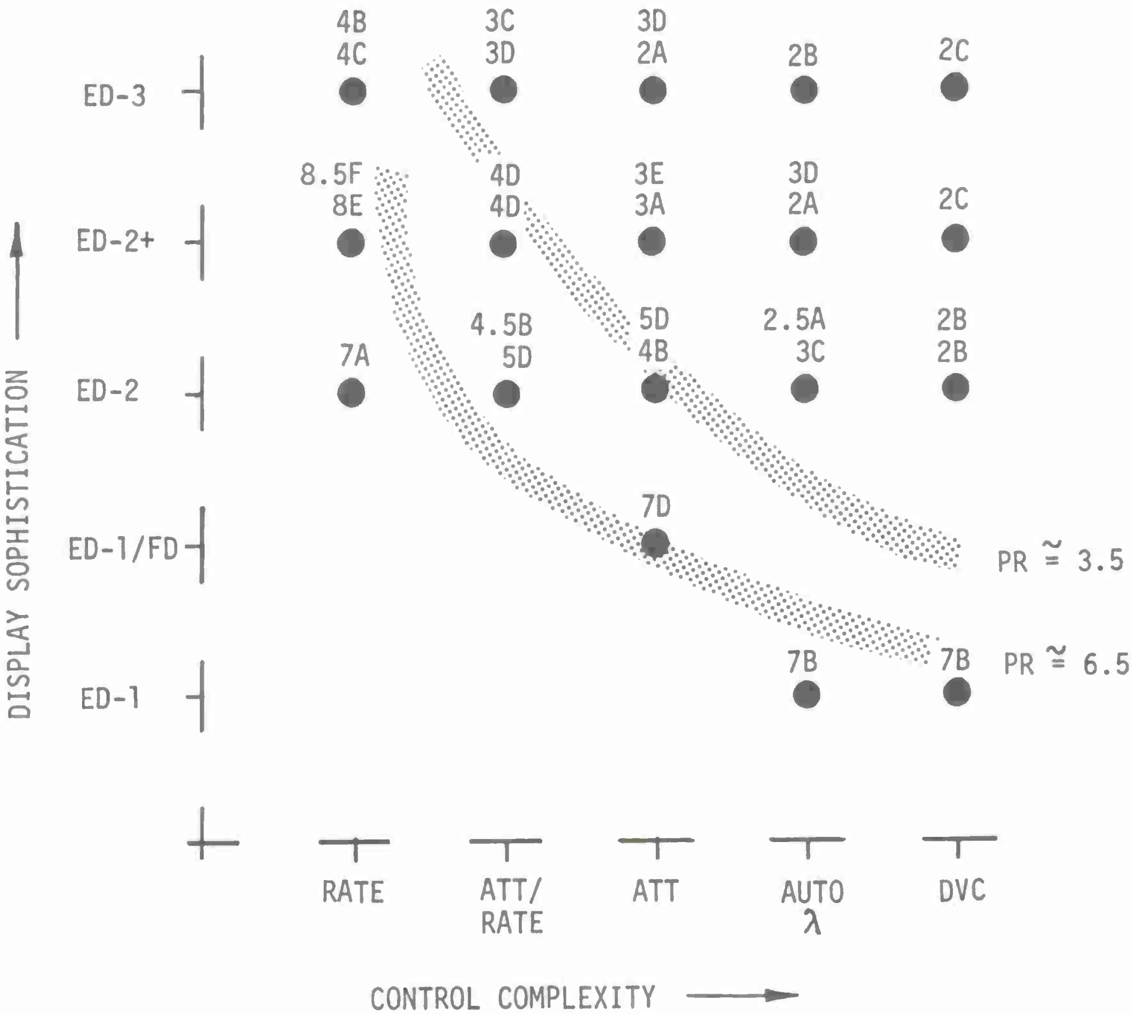


Figure 9-1 PILOT RATING DATA FOR PRIMARY MATRIX (NO CROSSWINDS, WITH ITVIC)

characteristics (ATT/RATE) may be compensated by including a director to aid the pilot in this axis, while reducing the control demands on the pilot (AUTO) allows him to concentrate more thoroughly on glide slope control so that the need for a collective director disappears.

Another general result apparent from Figure 9-1 is the fact that, for a satisfactory (or even adequate: PR $\leq$ 6.5) system, the display must include velocity status information explicitly, regardless of the control system complexity (to the extent considered in this experiment). This result corresponds to Dukes' findings (Reference 14), and is a function both of the need to know translational drift velocities accurately in the hover for touchdown and of the requirement to change glide slope angle (level off) while decelerating, as is evident from the pilot comments:

AUTO:ED1 -- "Commanded level off at 100 feet is impossible. You can't get enough information quickly enough there: I overshot dramatically and think we would have hit the ground. (Hover) very difficult without velocity display. You can't tell how fast the airplane is going or to where. Performance was very poor. A fantastic amount of thought process was required." (F-124)

DVC:ED1 -- "Both approaches I flew through the 100 feet level off altitude. (Hover) very poor because of no velocity information. You would never know when you got the drift killed in either direction. Don't think I could land it." (F-141)

The pilot compensation required without explicit velocity information remains intolerable even when control director information is added to a separate display; the ATT:ED1/FD configuration, selected because of its correspondence to that used in the NASA VALT experiment, demonstrates this point. In the NASA experiment, touchdowns were performed without velocity status information, using only control-director and horizontal position information, but the conclusion was that the system "was not adequate for operational use" (Reference 5); the pilot rating of 7 (adequate performance not attainable with tolerable pilot workload, controllability not in question) obtained for the ATT:ED1/FD configuration corroborates this result, and the pilot comments explain why.

ATT:ED1/FD -- "(Hover) is particularly bad. Could not be precise because you can't tell what the airplane is doing. You can not derive velocity information just from the relative motion of the airplane and pad symbols. About all you can do is get it stopped. (Landing) impossible. You need to know the small longitudinal and lateral velocities, which aren't on the display." (F-121)

A final general result that can be seen in Figure 9-1 is the fact that, as long as velocity information is given to the pilot on the display, no trend of pilot rating with display sophistication is evident for the decoupled velocity control system (DVC). This result indicates the advantage of providing the pilot with augmented and at least partially decoupled control over the two velocity components of major interest plus eliminating the need for manual configuration changes; if "good" airplane response characteristics relative to the task are provided, the details of the displayed information become less important to satisfactory system performance. It is, in fact, interesting to note that one of the DVC:ED2 evaluations shown in Figure 9-1 had been intended to be the DVC-ED2+ combination, which adds a collective stick director to the display, and the pilot was so briefed (recall the set-up procedures described in Section 8.3); because a potentiometer was not set, however, the ED2 format resulted instead, in which the vertical axis circular symbol is vertical velocity error instead of a collective stick director and hence requires a different control technique to null the altitude error. This mistake was discovered at the conclusion of the second approach prior to the pilot comments and rating, and these comments demonstrate the decreased importance of the display details:

DVC:ED2 -- "(Interception) easy to tell when you should start down. It wasn't as easy as it should have been because a pot was missed, didn't get collective director information. Still was able to fly the thing O.K. (Tracking) OK, didn't get far off. Collective didn't seem to be following well...(but) still had a good, I thought reasonable, profile. Airplane is acceptable, it is satisfactory without improvement. I probably would have done better if I had had some idea of what to do with the collective, but that part didn't bother me at all surprisingly enough." (F-141)

Within those configurations considered satisfactory, several important points should be noted. First, pitch and roll control directors are not required for satisfactory performance with an attitude command system as implemented in this experiment; although Dukes' helicopter simulations demonstrate a similar conclusion for the hover task (Reference 14), until this X-22A experiment it was thought that full control command information would be required for satisfactory decelerating instrument approaches (Reference 5). Precise pitch and roll attitude control is clearly of fundamental importance for the instrument task considered in this experiment: pitch attitude is the primary command for vernier velocity control during the deceleration, and roll attitude precision requirements, as will be discussed shortly, become increasingly demanding as speed decreases to maintain heading tracking. Given the importance to the pilot of attitude control, the question is therefore the extent to which the control augmentation can reduce the requirement for additional display information devoted to aiding him in this regard; the pilot comments for configurations ATT:ED3 and ATT:ED2+ show the mildly unpleasant increase in pilot compensation required when pitch and roll control directors are not included, but also

demonstrate a satisfactory situation exists without them if attitude command in pitch and roll is provided:

ATT:ED3 -- "(Tracking) very easy task, good information. Aircraft is controllable, acceptable, satisfactory. Pilot compensation is not a factor: it's amazing how you can relax with this one." (F-131)

ATT:ED2+ -- "Aircraft response good, seemed to have a little problem with bank attitude control, but very minor. Both localizer and glide slope (tracking) really very easy, good precision control. Controllable, acceptable, satisfactory. Slight problem with bank attitude control is a mildly unpleasant deficiency although minimum pilot compensation is required. Maybe I'm being a little harsh". (F-131)

A second point that can be seen in the satisfactory configurations concerns the control of vertical position and velocity for glide slope tracking. As has been discussed, the low inherent height damping of most VTOL aircraft results in control of the vertical axis becoming a major problem: the CL-84 experience is a good example (Reference 16). For this X-22A experiment, none of the control systems except DVC included augmenting the height damping of the basic X-22A; instead, increases in displayed information for this axis (i.e. collective stick control director) were considered as a variable (ED2+ vs. ED2), as was increasing the automaticity of the control system (AUTO vs. ATT). The ratings demonstrate that, if the pilot has the control job of performing the duct rotation (configuration change) manually, the collective director is necessary to reduce the workload in that axis for the system to be considered satisfactory; if, however, as was discussed with regard to the interactive effects, the pilot is relieved of the duct rotation duty, he may perform the glide slope tracking satisfactorily using only vertical velocity and position error information. If both a collective director and the increase in automaticity are provided, then the pilot's workload is reduced sufficiently that vertical control can become more precise:

AUTO:ED2+ -- "Glide slope much easier to control with automatic duct rotation because left hand has only one job to do. When I do the duct rotation (manually), collective control is not as precise. Collective is no problem -- good control since don't have to worry about duct rotation. Pilot compensation not a factor for desired performance." (F-131)

Turning to those combinations rated adequate but unsatisfactory ($3.5 \leq PR \leq 6.5$), the data are useful primarily for noting trends as either display sophistication or augmentation complexity is reduced from the level required for a satisfactory system. First, note that acceptable system performance is possible with rate augmentation only (when crosswinds

are not informed) if the display includes integrated full control director information (RATE:ED3). Such a combination is unsatisfactory primarily because of attitude control problems in the hover, even with the stabilization commands provided by the pitch and roll directors. Although rate commands are generally preferred for up and away flight, and were generally satisfactory for the initial tracking, pilot comments indicate a tendency to overcontrol in pitch when attempting to move around the landing pad, and a preference for force feedback from the controls to help know the attitude during instrument hover:

RATE:ED3 -- "Glide slope and localizer tracking very easy tasks. The needles act like a flight director should, and it is very natural. (Hover) a bit of a problem. Tendency to overcontrol pitch because displayed motion (translation) reacts so slowly and I kept wanting to move aircraft. Don't get force feedback to help with the attitude, and attitude was more of a problem with this configuration. Up and away it's very good. I'm going to downrate it for the hover, however; I think there is a real tendency to overcontrol it in hover. I may even be a little easy on it." (F-121)

The importance of good control and display characteristics for pitch and roll attitude is also emphasized by the degradation in rating of the pitch attitude/roll rate command system when the pitch and roll stick control directors are removed (ATT/RATE:ED2+ vs ATT/RATE:ED3). As was mentioned earlier, roll attitude precision becomes increasingly important for control of heading as velocity decreases: if sideslip is essentially held zero (the function of the ATC directional mode), then for small attitudes yaw rate may be expressed as:

$$r \cong \frac{g}{V_o} \phi \qquad (9\text{-}1)$$

This influence on heading control was noted in an earlier X-22A program when it was found that roll mode time constant requirements were more stringent than anticipated because of the STOL approach speed (Reference 11). With rate command in roll and no roll control director (ATT/RATE:ED2 or ATT/RATE:ED2+), pilot comments in the current experiment note similar difficulties, whereas including a roll control director provided a satisfactory system:

ATT/RATE:ED2 -- "Kept putting in more bank and getting more turn than I wanted. Had to use ADI to figure out bank." (F-133)

ATT/RATE:ED2+ -- "Localizer tracking not as easy as desired because of tendency to overbank aircraft." (F-132)

ATT/RATE:ED3 -- "Some problem overbanking the aircraft, but that dissipates when I'm tracking the vertical bar closely." (F-142)

It is interesting to note in this regard that, if the bank attitude control problem is addressed with a control director rather than providing attitude command control augmentation, system acceptability is very sensitive to the design logic. Appendix V contains pilot comments for an evaluation of the ATT/RATE:ED3 configuration which is not included in Figure 9-1 because the roll control director gain was set at a lower value than called for (by a factor of 1.75): the pilot rating was 6, and the comments explain why:

ATT/RATE:ED3 (Wrong VBAR) -- "Strong tendency to overbank. Continuous roll inputs either for small stability problem or just overcontrolling the airplane." (F-133)

This group of results indicates that the roll attitude control problem is quite important to the decelerating instrument task, and that providing rate-command-attitude-hold augmentation for roll, at least as implemented in this experiment, may provide a system that is only marginally satisfactory.

A final result that can be seen from these adequate-but-unsatisfactory configurations relates again to the vertical axis: difficulties in maintaining precise control of glideslope are responsible for the degradation to unsatisfactory of the attitude command control system and the further degradation of the attitude/rate system when the collective stick control director is removed from the display (ATT:ED2 vs. ATT:ED2+ and ATT/RATE:ED2 vs. ATT/RATE:ED2+):

ATT/RATE:ED2 -- "On the deceleration I kept trying to lead altitude but I kept overcontrolling it and the need to do the manual rotation made me less precise." (F-133)

ATT:ED2 -- "The deceleration causes a problem because I undershoot altitude. It's more work at the end to control altitude than I like, and I tend to get behind on the approach path. Altitude control should be better, I have to devote too much time to it." (F-123)

Considering finally those combinations considered inadequate for the task (PR > 6.5), two important results are apparent. First, as has been discussed, adequate performance with a tolerable pilot workload is not possible if velocity information is not displayed explicitly. Second, the rate augmentation system is unacceptable if pitch and roll control directors are not provided; as would be expected, control of pitch and roll attitude during the deceleration and hover requires an intolerable level of pilot compensation if stabilization commands are not explicitly provided:

RATE:ED2 -- "Tracking easy. Hover really a problem. Hard to get enough attitude information from electronic display. Performance very poor, got large attitudes trying to get over spot. (Could not land.) Poor attitude control makes airplane move left and right too quickly." (F-124)

The pilot rating data shown in Figure 9-1 include evaluations in which the influence of turbulence ranged from none (Turbulence Effect Rating TER=A) to major (TER=F). It should be noted that the TER was used by the pilot in this experiment as an indication of turbulence effects only: in particular, the increased difficulty in crosswinds is not reflected in the TER, and is discussed separately in Section 9.2.2. As can be seen, except for the rate augmentation system, there was little effect of turbulence on the Cooper-Harper pilot rating for a given configuration. The pilot comments cited in the previous paragraphs were selected from evaluations in which the influence of turbulence was considered minor (TER=A,B,C), and may be compared to the comments obtained from repeat evaluations in which turbulence was considered an at least moderate influence to ascertain the qualitative effects of turbulence. The major effect appears in comments concerning degraded heading tracking; the primary reason for this apparent effect is that lateral gust inputs generate quite high lateral accelerations in the X-22A (high side force derivative Y_β), which feed through the complementary filters as a change in estimated lateral velocity (see Figure 4-1 in Section IV) and therefore rotate the displayed velocity vector. Pilot comments taken from evaluations in turbulence for some of the configurations discussed earlier note this effect on both the velocity vector and the roll stick control director (which uses $\hat{Y}_h$ in its command logic, Section VI):

ATT/RATE:ED3 -- "Localizer tracking a problem because turbulence oscillates aircraft in roll and vertical bar quite sensitive. Turbulence inputs move the bar too much. Tendency is to lag vertical bar to see if movement is caused by turbulence and therefore get behind on localizer. (It's) a mildly unpleasant deficiency, but requires only minimum pilot compensation." (F-128)

ATT:ED2+ -- "(Tracking) quite a bit of work because of gusts, turbulence. Heading would wander around when I wasn't banking the aircraft and I tended to disbelieve it. I could keep it under control but it was confusing." (F-134)

AUTO:ED2+ -- "Localizer tracking difficult. Velocity vector rotating back and forth. Can't decide if its a display sensitivity problem or something the aircraft is doing that isn't my fault due to wind shears or turbulence." (F-134)

9.2.2 Crosswind Configurations

Although acceptable system performance for the rate augmentation/full control director combination (RATE:ED3) had been predicted by the ground simulations prior to flight and verified in flight when low headwinds were present, pilot comments in the evaluations noted that control of heading, without the dual-mode directional system used in the more complex augmentation schemes, required additional attention in the hover:

> RATE:ED3 -- "(In hover I had) problem with the heading and knowing which way to go. The director needles didn't seem to help. I don't like the rudders and I had some problems interpreting the display in the hover." (F-108)

Since this problem would be exacerbated if the pilot were required to perform large heading changes in order to line up with the wind, the repeat evaluations were performed in the presence of winds primarily across the desired course. (Section 7.3.2). The resulting data are shown in Figure 9-2. As can be seen, the RATE:ED3 configuration now does not permit adequate performance with tolerable pilot compensation (PR = 7), and the reason is that, as hypothesized, the pilot was unable to get the aircraft pointed into the wind and hence could not eliminate drift velocities:

> RATE:ED3 -- "(Hover is) very depressing. Can't get heading rotation and bank angle problems solved and get airplane back over spot. Pitch control gets bad because of concentration on bank and heading, get ± 15 degree pitch changes. Not possible to do the job." (F-130)"(Hover is) biggest problem because of having to solve the heading problem. Had it solved on first approach, drifted off the spot on the second. Hover performance very, very poor, not acceptable." (F-140)

The two configurations with the attitude command control system (ATT:ED3 and ATT:ED2+) did not show a similar degradation in crosswinds because of the dual-mode directional augmentation system. As will be recalled, when the turn-following (ATC) mode is selected with this system, the directional axis control system attempts to maintain zero sideslip; hence, during an approach in a crosswind, the airplane tends to stay pointed into the relative wind automatically. This characteristic, coupled with the improvement in pitch and roll attitude control given by the attitude command augmentation, reduces the pilot's workload sufficiently to make the wind problem in hover only uncomfortable:

ATT:ED3 -- "Display and aircraft control were not problems in hover, but inability to determine precisely what winds were doing was a problem. Winds were variable, and on second approach it seemed to be at my back, got high trying to sort it out. Performance was acceptable though uncomfortable. It's acceptable, I think it's satisfactory under the conditions we're flying today. I could do the job even though it's uncomfortable in the hover with the winds varying the way they were." (F-139)

ATT:ED2+ -- "(Hover) not a problem. Performance good, display good. Got smarter about trying to figure out what wind was doing. Only (tracking) problem is that crosswind requires more and more heading change as get closer to ground to keep up with localizer, which can overload you. It causes you to have more work to do. Airplane is acceptable and satisfactory without improvement. Main reason for half rating is that the tendency to get overloaded at bottom where I have to worry about heading is a slightly more than negligible deficiency." (F-140).

The results indicate that a display of wind direction to the pilot, which was not investigated in this experiment, would be very useful; it is possible that having this information could alleviate to a large extent the degradation in ratings for the RATE:ED3 configuration when the crosswind component is large relative to the headwind component. It is necessary, however, to have the control system perform the pointing function when this information is not displayed.

9.2.3 No-ITVIC Configurations

The data presented in Figures 9-1 and 9-2 and discussed in the preceding subsections were all obtained using the Independent Thrust Vector Inclination Command (ITVIC) director light, either to command the pilot to perform configuration changes when manual duct rotation was required, or as status information when the evaluation configuration included automatic rotation. As was discussed in Section 7.3.3, it had originally been planned to devote several repeat evaluations to investigating the effects of removing the ITVIC director. In point of fact, the first two repeats, coupled with pilot comments regarding the necessity of having the ITVIC for several of the evaluations in the primary matrix, were sufficient to demonstrate the requirement for this display and obviated the usefulness of any further investigation. The two configurations evaluated in repeats without the ITVIC director were ATT:ED3 and ATT:ED2; the pilot rating in each case was a 6, which in the case of the ATT:ED3 configuration, is a degradation from a system that is satisfactory (PR = 3) with the ITVIC to one which is barely adequate (PR = 6)

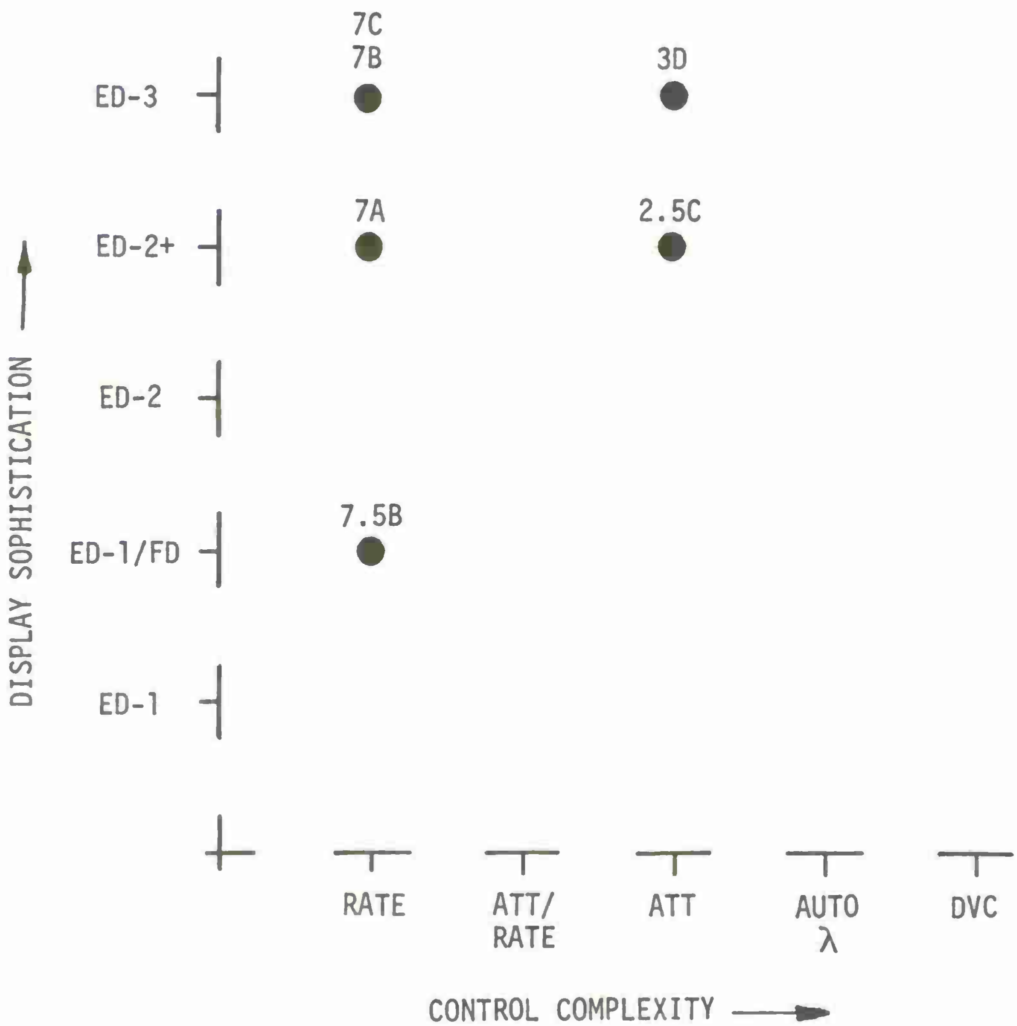


Figure 9-2 PILOT RATING DATA FOR CROSSWIND MATRIX (WITH ITVIC)

without it. The pilot comments for these two evaluations reveal that the increased compensation required in deciding when to rotate the ducts without the ITVIC results in poor tracking performances through the deceleration:

ATT:ED3 (No ITVIC) -- "Both localizer and glide slope tracking suffer because of concentration in determining when to rotate ducts. Have to spend time looking at duct angle and velocity to keep a good profile, and there isn't enough nformation to do that easily. Lack of the ITVIC director is a serious problem. I think the job could be done. It's very objectionable, however, and your workload is very high." (F-123)

ATT:ED2 (No ITVIC) -- "Miss the ITVIC even though I thought on the simulator that I had the situation figured out and could do it. When I got off on the localizer, so the vector didn't pass through the diamond, then I get ahead or behind on the duct rotation. It's easy only if you're right on the localizer so vector passes through diamond." (F-128)

In addition to these comments when the ITVIC director was not present, it is clear that this command is considered mandatory in many instances to aid the pilot in performing the task, as can be seen from pilot comments for several of the configurations in the primary matrix:

AUTO:ED3 -- "ITVIC useful even with automatic rotation as status information and it coordinates with the forces caused by duct rotation, which is good information." (F-126)

ATT:ED3 -- "ITVIC is invaluable at this point in the program -- could not have kept up with peripheral instruments." (F-120)

ATT:ED2+ -- "ITVIC light mandatory as far as I'm concerned." (F-140)

ATT:ED1/FD -- "You must have the ITVIC light for this configuration -- would have no chance without it." (F-121)

ATT/RATE:ED2+ -- "Having ITVIC light is a good thing." (F-128)

RATE:ED3 -- "Needed the ITVIC light, don't think I would have stayed on the profile well without it." (F-108)

RATE: ED2+ -- "ITVIC light is a must." (F-130)

9.3 PILOT LOOP-CLOSURE CONSIDERATIONS

9.˜.1 Discussion of the Analysis Procedure

Although the pilot rating data and supplementary comments discussed in the previous subsection are the most viable method available for determining the suitability of a given aircraft/display combination for a specified mission or flight phase, it is frequently useful to consider also mathematical representations of the pilot in the closed-loop aircraft/display/pilot system. Pilot-modeling analyses can be directed toward two general types of goals:

- Provide additional insight into the reasons for the pilot rating by attempting to model what the pilot actually does to achieve satisfactory or adequate performance.

- Provide design guidance for future systems by attempting to relate selected characteristics of the analysis to observed trends in pilot rating.

It is philosophically appealing to achieve the second goal by initially considering the first one: that is, if one can compute pilot compensation terms equivalent to what the pilot must do to achieve a level of performance that is assumed to be satisfactory or adequate, then the amount of compensation required and the performance achieved should correlate with pilot rating*. Most of the many possible methodologies that are available for performing analytic pilot-in-the-loop investigations attempt to meet both the goals in this manner.

The more well-known pilot-modeling techniques may be generally clasified by the criteria assumed as the basis for determining the amount and type of pilot compensation required, such as open-loop (e.g. Reference 41) or closed-loop (Reference 47) frequency response performance criteria, "optimal" weighting of an assumed pilot rating index which contains both compensation and performance terms (Reference 48), or an "optimal" model of the pilot/aircraft system performance (Reference 49). In all cases, the objective is to determine what the pilot <u>actually does</u> (that is, the structure of the pilot model and the values of the compensation terms in it) to meet the hypothesized criterion on

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* The Cooper-Harper pilot rating scale attempts to focus the pilot's decision-making process on the trade-off between workload and performance. This trade-off in terms of <u>measured</u> performance and workload indices for this experiment is discussed in Section X.

what he is actually trying to achieve (generally stated as either a desired or "optimal" performance level, or in the case of Reference 48, as a performance level weighted by the amount of compensation required). The correlation of the resulting pilot model (and performance) parameters with pilot ratings to provide design guidance, however, becomes increasingly less successful as the model gets more complex; the basic problem is that the pilot model parameters depend entirely on the assumed achievement criterion, and the diversity of these criteria, coupled with the inherent difficulty of selecting representative forms of them to start with, results in only a limited capability to provide design guidance by considering the actual pilot structure for each situation.

For the pilot-in-the-loop analysis of the data from this experiment, therefore, an approach which does not attempt to model the actual pilot behavior and resulting closed-loop characteristics is used. The intent of the approach is to examine the best performance that would be possible for a given control-display combination if the pilot performed <u>no</u> compensation, and to infer from the differences in achievable performance under this constraint the suitability of the combination. Philosophically, the performance/workload tradeoff is attacked from a different standpoint than that discussed above: rather than solve for the pilot compensation required to achieve a performance level which is assumed to represent what the pilot wants, the performance level that he could achieve with no compensation is computed. This approach is justified by noting in the Cooper-Harper scale that for a system to be rated satisfactory ($PR \leq 3.5$), pilot compensation is either minimal or not a factor to achieve the desired performance; all of the pilot-modeling techniques mentioned in the previous paragraph also lead to the "best" system being one in which the pilot model structure includes no compensation terms; the underlying assumption of the analysis, therefore, is probably less tenuous than a performance hypothesis, and the analysis itself becomes quite simple. It is emphasized, however, that the results will be only a qualitative indication of whether or not a system is satisfactory: since pilot compensation is not explicitly considered, systems for which adequate performance is attainable with tolerable pilot compensation ($3.5 < PR \leq 6.5$) are not directly separable from those for which adequate performance cannot be obtained ($PR > 6.5$), although trends in the achievable performance may indicate this distinction.

The "comfortable" (no compensation) pilot model is defined as a gain plus pure time delay ($CPM \triangleq Ke^{-\tau s}$), and was used in the design of the Decoupled Velocity Control system discussed in Section V. For application to the control-display combinations investigated in this experiment, it is necessary to decide upon "primary" control loops and define what will be meant by "best" performance achievable. If the pilot comments discussed in the previous subsection and presented in Appendix V are considered, the pilot's concerns in controlling the aircraft appear to be as follows (from most important to least important for two elements of the task):

Decelerating Approach:

- Pitch and roll attitude stabilization and control
- Vertical (glide slope) tracking

- Localizer tracking
- Velocity (deceleration) tracking
- Yaw attitude control

Hover:

- Pitch and roll attitude stabilization and control
- Longitudinal and lateral velocities
- Yaw attitude control
- Longitudinal, lateral position
- Vertical velocity
- Vertical position

For the "command" display formats investigated in this experiment (ED-3, ED-2+, and ED-2) it is reasonable to consider directly the loop closures between a given display error (e.g. control director displacement for ED-3, longitudinal and lateral velocity error for ED-2) and a single controller (e.g. collective stick for vertical velocity) if attention is focussed on the decelerating descent (characteristics at $\lambda = 50^{\circ}$, 65 kt) and hover. No assumptions about the pilot obtaining "implicit" information from the display (e.g. translational rate from the movement of a position error symbol) are considered because that implies pilot compensation. For the attitude command control system (ATT), pilot comments indicate no stability problems in either pitch or roll, and so attitude loop closures are not used for this control system. For both the rate augmentation system (RATE) in both pitch and roll, and the pitch-attitude/roll-rate command system (ATT/RATE) in roll, however, it is clear from the comments that "inner" loop attitude closures need to be considered also when control directors are not included in the display:

ATT:ED2+	--	"Airplane response not a factor, very stable. Aircraft seems very well attitude stabilized - levels itself out if I take my hands off, which is quite comfortable." (F-134)
ATT/RATE:ED2	--	"Lateral (response) a problem -- a real tendency to overbank. Had to use (ADI) to figure out bank angle." (F-133)
RATE:ED2+	--	" Can't get good enough pitch and bank attitude information off electronic display, had to use ADI as primary instrument. By putting primary emphasis on attitude control I at least got to the (hover) spot." (F-134)

For the RATE and ATT/RATE systems, therefore, the achievable performance both with and without attitude loop closures is considered.

For the analysis as considered here, the "best" performance is defined as closed-loop bandwidth, which in turn is selected as the frequency at which the closed-loop frequency characteristics exhibit either a 3 dB amplitude change from the steady state or at which the closed-loop phase angle becomes -90 degrees, whichever is lower. Although arbitrary, this measure of performance corresponds to the hypothesized performance criteria used in some previous work (e.g. Reference 47). To determine this performance for a particular control axis of a selected control-display combination, the following simple procedure is followed:

(1) If an inner attitude loop is to be considered, the open-loop attitude-to-stick Bode plot is used to determine the gain which will give a closed-loop attitude response bandwidth of approximately 2 rad/sec (comparable to those provided with the ATT control system). This gain and the Padé approximation to a time delay of 0.3 seconds are then used to compute the augmented inner loop roots which are used in the following steps. If an attitude loop closure is not considered, the transfer functions of the aircraft for the chosen control system are used in the following steps.

(2) The open loop display-control transfer function of interest (e.g. HBAR/δ_{es} for the ED-3 format and rate augmentation control system) is multiplied by a pure time delay ($e^{-\tau s}$, $\tau = 0.3$) and the Bode frequency response computed.* From this response, the gain which will provide a phase margin of at least 30 degrees <u>and</u> a gain margin of at least 4 dB is found. The values of phase and gain margin again correspond to conventional practice, and are used to ensure a reasonably low closed loop resonance ($< \sim 6$ dB).

(3) Using the gain value found in Step 2, the closed loop Bode frequency responses are calculated, assuming the pilot to be a gain (at this value) plus pure time delay ($e^{-.3s}$). The closed-loop bandwidth (gain change of 3 dB or phase angle of -90°, whichever frequency is lower) is then found from this plot.

Figure 9-3 gives an example of the procedure applied to the longitudinal velocity tracking (ED-2+ or ED-2) with the rate augmentation system. The results of considering various loop closures in this fashion to selected configurations from Figure 9-1 are discussed below.

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* The Padé approximation is not used in any steps except the computation of modified attitude response roots when a pilot-supplied attitude loop closure is assumed.

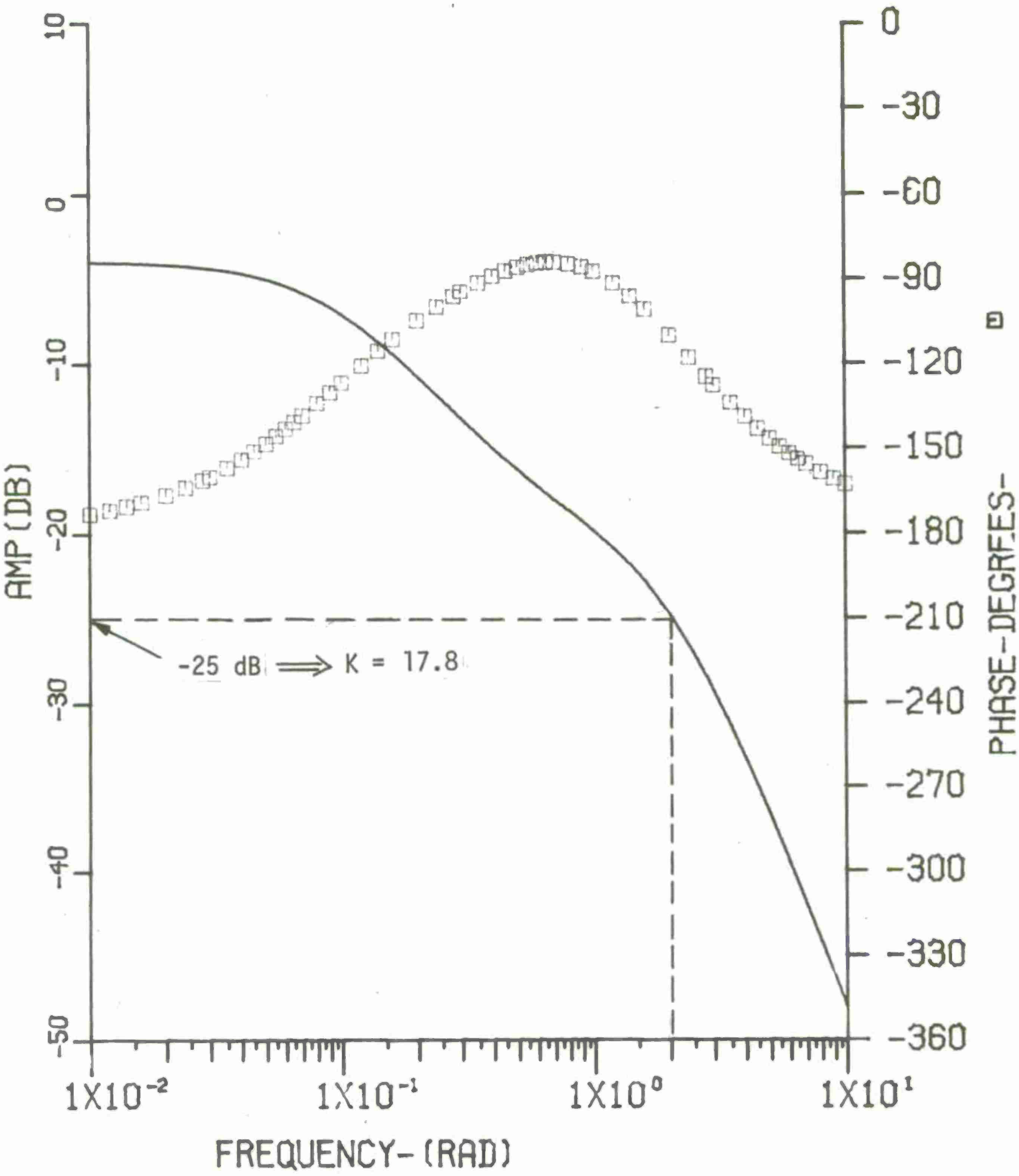

Figure 9-3a DETERMINATION OF INNER-LOOP θ/δ_{es} GAIN FOR RATE:ED-2 LONGITUDINAL VELOCITY TRACKING FROM PLOT OF $\theta(s)/\delta_{es}(s)$

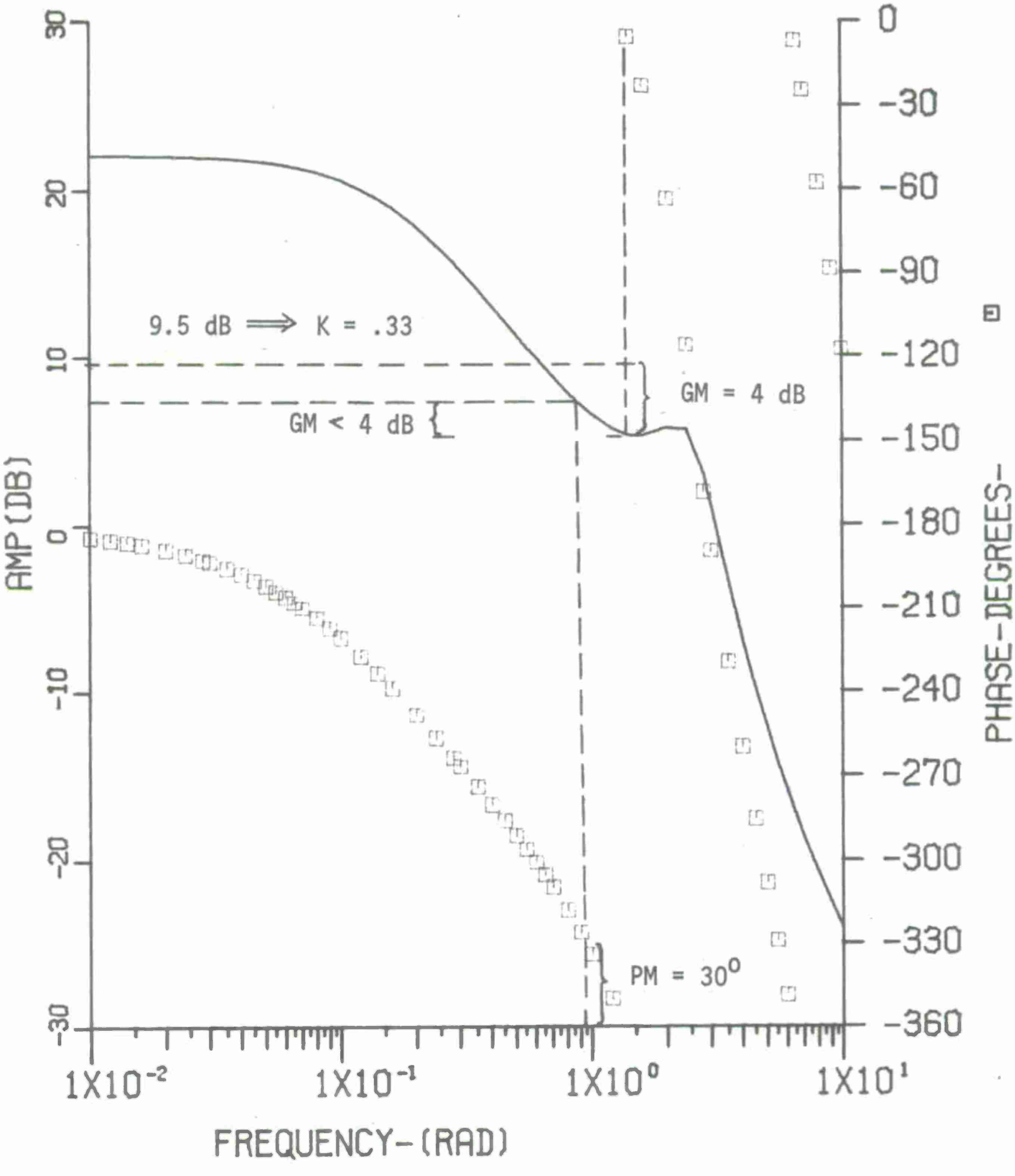

Figure 9-3b DETERMINATION OF OUTER-LOOP u/δ_{es} GAIN FOR RATE: ED-2 LONGITUDINAL VELOCITY TRACKING FROM PLOT OF

$$e^{-.3s}\left.\frac{u(s)}{\delta_{es}(s)}\right|_{K_\theta = 17.8}$$

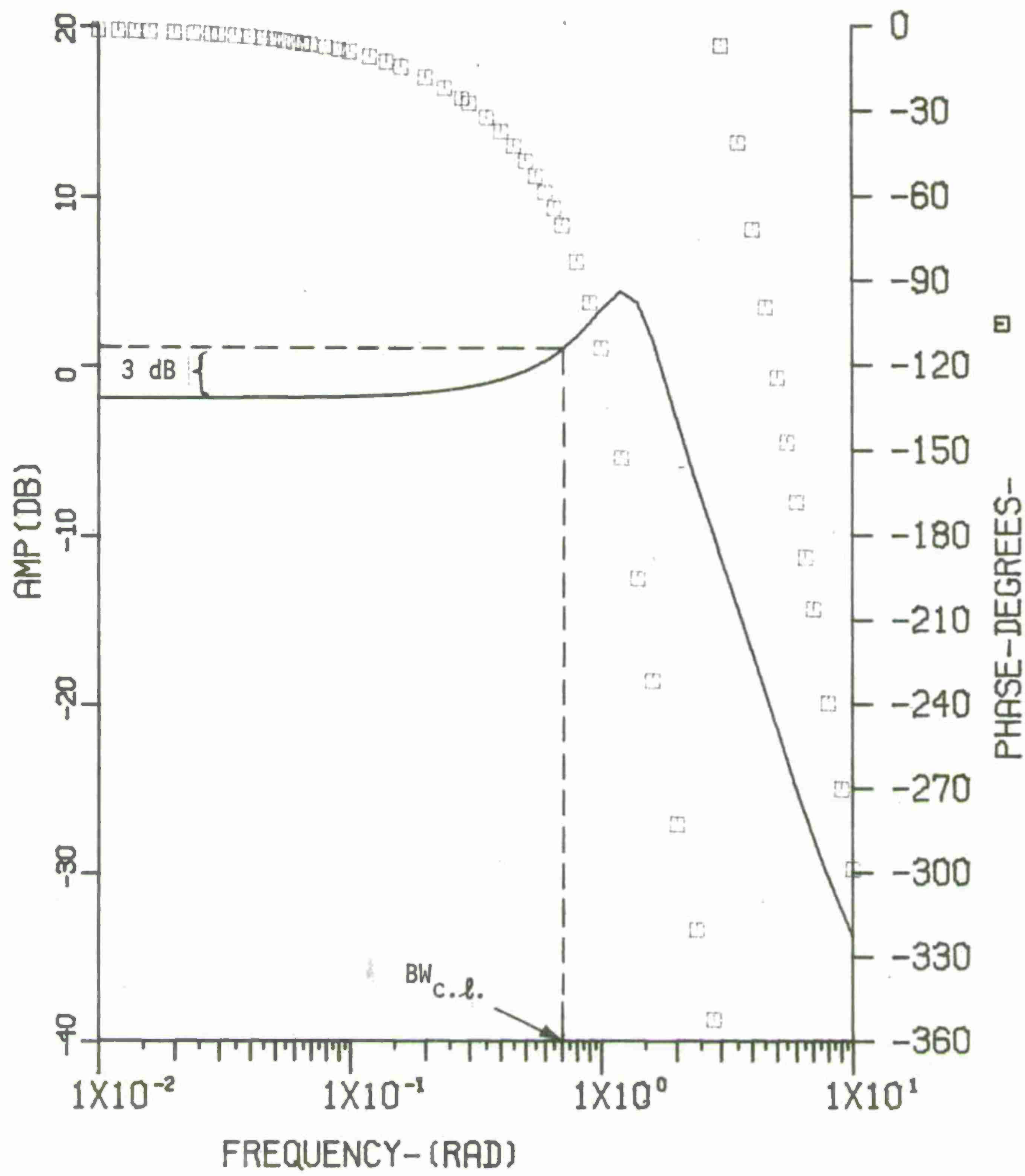

Figure 9-3c DETERMINATION OF CLOSED-LOOP BANDWIDTH FOR RATE:ED-2 LONGITUDINAL VELOCITY TRACKING FROM PLOT OF

$$\frac{.33e^{-.3s} \left.\frac{u(s)}{\delta_{es}(s)}\right|_{K_\theta = 17.8}}{1 + .33e^{-.3s} \left.\frac{u(s)}{\delta_{es}(s)}\right|_{K_\theta = 17.8}}$$

9.3.2 Discussion of Loop-Closure Results

The specific loop-closures considered for this analysis were as follows:

- Longitudinal stick
  - HBAR/δ_{es} for ED-3
  - u/δ_{es} for ED-2+ and ED-2
- Lateral stick
  - VBAR/δ_{as} for ED-3
  - $(u_o \psi + v)/\delta_{as}$ for ED-2+ and ED-2
  - $\frac{1}{s}(u_o \psi + v)/\delta_{as}$ for ED-1
- Collective stick
  - VTAB/δ_{cs} for ED-3 and ED-2+
  - h/δ_{cs} with $\dot{h}/\delta_{cs}$ inner loop closed for ED-2
  - h/δ_{cs} for ED-1

These closures, assuming a "comfortable" pilot model ($CPM \triangleq Ke^{-\tau s}$), were performed as described above at both λ = 50° (65 Kt) and λ = 90° (0 Kt) for the majority of the evaluation configurations shown in Figure 9-1; Table 9-1 summarizes the closures considered.

Table 9-1

LOOP-CLOSURES PERFORMED

	δ_{es}	δ_{as}	δ_{cs}
RATE:ED3	X	X	X
RATE:ED2	X	X	X
ATT/RATE:ED3		X	
ATT/RATE:ED2		X	
ATT:ED3	X	X	X
ATT:ED2	X	X	X
ATT:ED1		X	X
DVC:ED3			X
DVC:ED2			X
DVC:ED1			X

The ED-2+ format closures correspond to those of ED-2 for longitudinal and lateral stick and to ED-3 for collective stick and hence are not shown; similarly, the longitudinal and collective stick closures for the ATT/RATE system are the same as for the ATT system, the lateral stick closures for the DVC system are the same as for the ATT system, and all the AUTO λ closures are the

same as the ATT system. The longitudinal stick closures for the DVC are not considered since duct angle is the primary velocity control and rotation is automatic.

The computed closed-loop bandwidths in rad/sec are summarized in Table 9-2 for the cases considered.

Table 9-2

DERIVED CLOSED-LOOP BANDWIDTH (rad/sec)

	Control:Display	$\lambda = 50^{\circ}$	$\lambda = 90^{\circ}$
Vertical	RATE:ED3	$.08 \Rightarrow 2.5$	2.5
	RATE:ED2	1.4^{+}	1.5^{+}
	ATT:ED3	2.5	2.5
	ATT:ED2	1.4^{+}	1.6^{+}
	ATT:ED1	0.3	0.1
	DVC:ED3	1.7	3.0
	DVC:ED2	1.7^{+}	1.7^{+}
	DVC:ED1	0.8	0.7
Lateral	RATE:ED3	$0.1 \Rightarrow 2.2$	$0.05 \Rightarrow 2.1$
	RATE:ED2	0.45^{*}	0.85^{*}
	ATT/RATE:ED3	$.15 \Rightarrow 2.7$	$.60 \Rightarrow 3.0$
	ATT/RATE:ED2	2.0^{*}	1.0^{*}
	ATT:ED3	$.02 \Rightarrow 3.5$	2.5
	ATT:ED2	0.5	1.5
	ATT:ED1	U/S	0.2
Longitudinal	RATE:ED3	$0.11 \Rightarrow 3.5$	2.0
	RATE:ED2	0.70^{*}	1.10^{*}
	ATT:ED3	2.0	3.50
	ATT:ED2	0.65	1.05

Cases with two numbers are those for which a minimum pilot gain to achieve stability is also required; the lower number is the closed-loop bandwidth at the minimum gain. The designation "U/S" means that a stable closed loop system is not possible if only the given loop is closed without additional pilot compensation. Finally, the asterisks indicate those combinations for which the inner attitude loop was closed prior to computing the outer loop bandwidth, and the crosses those for which an inner altitude rate loop was closed.

Consider initially the bandwidths possible in the vertical channel. As can be seen, the use of a collective stick director (ED3, ED2+) allows a bandwidth on the order of 2.5 rad/sec both during the descent and at hover for all the control systems, the display of altitude rate and position errors (ED2) permits an altitude loop bandwidth of approximately 1.3 rad/sec (assuming an inner loop closure on altitude rate) for the RATE and ATT systems and of 1.7 rad/sec for the DVC at hover, and the display of altitude error only (ED1) results in an altitude loop bandwidth of less than 1.0 rad/sec. Note that the DVC control system permits an improved altitude bandwidth with the ED1 display over the ATT system because of the augmented height damping of the aircraft. These bandwidth performance measures which are possible with simple loop closures assuming little or no pilot compensation tend to reflect the pilot comments discussed in the previous subsection.

ED-3 or ED-2+ (BW $\cong$ 2.5 rad/sec):

ATT/RATE:ED3 -- "Collective is just a matter of following the bouncing ball, no problem." (F-142)

ATT:ED2+ -- "Collective control very good, simply follow the commands and very seldom overshoot or undershoot." (F-131)

ED-2 (BW $\cong$ 1.0 rad/sec)

AUTO:ED2 -- "Tend to lead the collective a little bit." (F-133)

ATT:ED2 -- "Altitude control should be better, I have to devote too much time to it. It's no more than a minor point." (F-123)

ED-1 (BW < 1.0 rad/sec)

AUTO:ED1 -- "Commanded level off at 100 feet is impossible. You can't get enough information quickly enough there." (F-124)

DVC:ED1 -- "Both approaches I flew through the 100 feet level off altitude." (F-141)

As has been discussed, the control of vertical position and velocity can be a major problem for VTOL aircraft with low inherent height damping. This simple analysis indicates that the primary control loop in this axis for a given control-display combination should permit a bandwidth of above 2.0 rad/sec to achieve the desired performance with no compensation; if the characteristics in the other control axes are sufficiently good so that closure of an inner altitude-rate loop may be considered only minor compensation, the resulting

bandwidth of approximately 1.3 rad/sec will still represent satisfactory performance. A bandwidth of less than 1.0 rad/sec would appear to be unsatisfactory.

Turning to the lateral channel, note first that the use of a lateral stick director permits maximum bandwidths on the order of 2.5 rad/sec for all the control systems with no pilot compensation (ED3). In each case, however, a minimum level of pilot gain to achieve system stability (which gives the lower bandwidth number) is also required to achieve system stability, which, for the forward flight case, is a result of basing the design on the hover characteristics (lateral velocity to lateral stick rather than $u_0\psi$) and, for the hover case, involves the imperfect cancellations at low frequency (see Section 6.5). For the ED-2+ and ED-2 formats, closure of the bank attitude inner loop is required for system stability with the RATE and ATT/RATE systems although not with the ATT system (since bank attitude is commanded directly); comparing the bandwidths in hover (which is where pilot comments indicate the problems to be), the RATE and ATT/RATE systems provide a bandwidth on the order of 1.0 rad/sec with the inner attitude loop closed, while the ATT system provides a somewhat higher bandwidth using only the outer loop. Again, the performance possible with simple loop closures reflect the trends shown by the pilot comments:

<u>ED-3 (BW $\cong$ 2.5 rad/sec)</u>

ATT/RATE:ED3 -- "Some problem overbanking the aircraft, but that dissipates when I'm tracking the vertical bar closely." (F-140)

ATT:ED3 -- "Used flight director all the way. The harder I worked at it the closer I kept it and the better job I did." (F-139)

<u>ED-2+ and ED-2 (BW $\cong$ 1.0 rad/sec for RATE, ATT/RATE; 1.5 rad/sec for ATT</u>

RATE:ED2+ -- "(Tracking a problem) at lower part. Big problem keeping up with bank angle, get off on localizer." (F-130)

ATT/RATE:ED2+ -- "(Tracking) some problem because turbulence seems to upset roll and so the diamond gets away from the end of the vector. Result is a bit more of a problem tracking both localizer and glide slope. Had to concentrate too much on the lateral." (F-128)

ATT:ED2+ -- "(Tracking) quite a bit of work because of gusts, turbulence. I could keep it under control but it was confusing." (F-134)

It appears that, for the lateral control, a bandwidth of greater than 1.0 rad/sec is required to represent satisfactory performance with no pilot compensation. Although this bandwidth can be approximated by the RATE and ATT/RATE systems in combination with the ED-2+ or ED-2 formats, it is necessary to close an inner bank attitude loop to do so, which may be considered as an increase in pilot compensation. It is worth noting in regard to this point that the attitude presentation on the electronic display in this experiment was considered difficult to interpret by the pilot, apparently because no shading below the horizon was used, and hence any control-display combination which required the additional process of closing an inner attitude loop to achieve a satisfactory performance tended to be considered as requiring moderate pilot compensation.

Considering finally the longitudinal tracking performance achievable, the trends are similar to the lateral channel. Again, the use of control directors allows a bandwidth greater than 2.0 rad/sec, while the ED-2 bandwidths are approximately 1.0 rad/sec, and require inner-loop attitude stabilization for the RATE system but none for the ATT system (or ATT/RATE, since the longitudinal axes of these two systems are identical). Again, it appears that an achievable bandwidth of greater than 1.0 rad/sec is required to represent satisfactory performance with no pilot compensation, and that for the RATE system, this level of performance requires the additional inner attitude loop closure.

9.3.3 Concluding Remarks

It is emphasized that the loop-closure analyses as discussed and applied to the results from this experiment in the preceding paragraphs represent an initial attempt to derive a simple means of interpreting the flying qualities results in terms of closed-loop pilot/aircraft/display characteristics, and are not intended to provide all the answers nor to replace the pilot ratings and comments as measures of system suitability for the task considered. For example, the level of performance of the RATE:ED3 configuration in terms of achievable bandwidth with no pilot compensation would appear satisfactory in all three control axes considered, and yet this configuration received pilot ratings of 4 or 7 depending on whether or not a crosswind was present (Figures 9-1, 9-2); the reason for the disparity is that the analysis did not consider control of heading in the hover (see the comments for the evaluation of this configuration on F-130), nor does it reflect the pilot's tendency to disregard the control directors during hover when he attempts to move around the landing pad (see F-121 comments).

In spite of the obvious limitations, however, the results of the analysis do demonstrate sufficient correlation with the ratings and comments to validate the procedure used when performing initial "quickie" design studies. It appears that, in general, the control-display combination under consideration should permit primary loop-closure bandwidths of at least 1.0 rad/sec for longitudinal and lateral tracking and 2.0 rad/sec for vertical tracking with no pilot compensation or inner-loop closures in order to be considered satisfactory when other control tasks (specifically configuration change) are present; if

the longitudinal and lateral loops are satisfactory and the pilot is aided by automatic duct rotation, it appears that the bandwidth required in the primary altitude loop can be reduced (and an inner-loop altitude rate closure used) for a satisfactory system. The closure of an inner attitude loop by the pilot is necessary for configurations in which either attitude command augmentation or control directors are not provided. By closing this inner loop, outer loop bandwidths approximately equal to those achievable with attitude command augmentation may be obtained. Although the performance would therefore be considered satisfactory, the inner loop closure was considered more than minor compensation for the task considered and the attitude display presentation used in this experiment, and hence these configurations were considered unsatisfactory.

Section X

RESULTS OF SYSTEM PERFORMANCE AND PILOT WORKLOAD ANALYSIS

10.1 SYNOPSIS OF SECTION

The purpose of this section is to present the results of an analysis of system performance and pilot workload for the various control/display combinations investigated and to interpret these results in a manner which both supplements and complements the flying qualities results discussed in Section IX. Accordingly, the first subsection reviews the framework within which these analyses are conducted, and the second subsection outlines the methodology employed and the selected performance and workload measures that were analyzed. The results of the analyses are then presented: first, the major independent effects of control system complexity and display sophistication are summarized, and then the combined control/display effects, as well as the influences of the ITVIC director, the task elements, turbulence, and crosswinds are discussed in a manner consistent with the structure of Section IX.

10.2 GENERAL DISCUSSION

In flying qualities research measures of pilot-vehicle performance and pilot workload are only meaningful when interpreted together as a means to substantiate and to quantify further the required tradeoffs of system performance and pilot workload indicated by the pilot evaluation data, i.e. the numerical Cooper-Harper pilot rating (PR) and pilot commentary. The Cooper-Harper pilot rating scale (Figure 8-4) emphasizes the interdependencee of task performance and pilot workload, both mental and physical, in the dichotomous decisions required for the selection of a numerical rating. Specifically, a "controllable" control/display combination may be assigned a numerical rating which places it in one of the three primary performance/workload categories (Reference 6):

- $1 \leq PR \leq 3$ — Desired, or at least clearly adequate, performance for the task is attainable (not necessarily "was attained") with a satisfactory level of pilot workload.
- $4 \leq PR \leq 6$ — Desired performance is not necessarily obtained; however adequate performance is attainable with pilot compensation (i.e. increased workload) up to the maximum tolerable level.
- $7 \leq PR \leq 9$ — Adequate performance is not attainable with maximum tolerable pilot workload; an excessive workload level would be required for adequate performance.

Because of the relative sophistication of even the least complex electronic display format, the evaluation pilot was provided with sufficient information by his instruments to evaluate pilot-vehicle performance throughout the evaluation task. To supplement the data provided by the assigned pilot rating, the pilot comment card requested specific information to aid the experimenter in identifying the area(s) which most heavily influenced the rating, e.g. control axis, phase of task, characteristics of the problem. Thus the pilot evaluation data gathered for this experiment is an important source of information regarding the interdependence and necessary tradeoffs of system performance and pilot workload.

In order to focus the results of the performance/workload analyses on these trade-offs, the discussion in this section is therefore divided into three primary categories:

- Major effects -- the independent effects of control system complexity and display sophistication on performance and workload during deceleration on the glide slope and level off are considered for the primary configuration matrix evaluations with a minor influence of turbulence (turbulence effect rating of A, B, or C).
- Interactive effects -- the interactive effects due to individual control/display combinations are considered for the same evaluations as above.
- Combined effects -- the effects of the final level deceleration to a hover, the crosswind evaluations, the No-ITVIC evaluations, and the evaluations with a moderate effect of turbulence are considered by comparison to the same evaluations as above.

Appendix VI discusses in detail the validity of this breakdown. The following subsection outlines the specifics of the performance/workload measures considered and the statistical analyses performed.

10.3 STATISTICAL ANALYSIS TECHNIQUE AND SELECTED INDICES

The experimental matrix presented in Section VII generally represents a 5 x 5 factorial experiment with multiple replications per test cell; that is, selected combinations of five levels of control augmentation and five levels of display sophistication were evaluated at least once with two approaches per evaluation. The advantage of this type of experimental design is that differences in performance and workload measures between control/display combinations may be identified as being due to any one, or a combination of, the following effects:

- control system complexity independent of display sophistication,

- display sophistication independent of control system complexity, or

- interactions of individual control system and display characteristics.

The experimental model for each performance and workload measure may be written in terms of three additive fixed effects and a random effect as follows (e.g. Reference 50):

$$Y_{ijk} = \mu + \tau_i + \theta_j + \gamma_{ij} + \epsilon_{ijk}$$

where Y_{ijk} = selected performance/workload measure for i^{th} row (or display), the j^{th} column (or control system), and the k^{th} replication in that test cell.

μ = universe mean of the selected parameter

τ_i = additive display effect

θ_j = additive control system effect

γ_{ij} = additive control/display interaction effect

ϵ_{ijk} = additive random effect.

Three sets of hypotheses are tested (where H_0 is the null hypothesis and H_a is the alternate hypothesis for each set):

<u>Interactive Effect</u> H_0: γ_{ij} = 0 for all i and j

H_a: γ_{ij} are not all = 0

<u>Display Effect</u> H_0: τ_i = 0 for all i, i.e. the row means are all equal.

H_a: τ_i are not all = 0.

<u>Control Effect</u> H_0: θ_j = 0 for all j, i.e. the column means are all equal.

H_a: θ_j are not all = 0.

Each null hypothesis is either accepted or rejected based upon the results of statistical F tests; these tests involve a comparison of ratios of the variance due to the interactive, display, and control terms in the model to the variance due to the random error term with a value of F determined both by the degrees of freedom of each variance ratio and by a selected level of significance (α). A variance ratio larger than the corresponding F value results in a rejection of the null hypothesis at the selected value of α and an acceptance of the alternate hypothesis. For example, a rejection of the control effect null hypothesis based upon an F test at α = .01 and the resultant acceptance of the alternate hypothesis establishes the existence of statistically significant differences in performance/workload due to variations in control system complexity independent of the level of display sophistication with only a 1% probability that significant differences due to variations in control system complexity alone do not exist.

This technique, based upon the statistical analysis of variance (ANOVA), was used to determine the existence, and cause of, significant differences in the performance and workload measures to be given below. The detailed results are presented in Appendix VI.

The measures of performance and workload selected for analysis using the ANOVA technique were obtained by processing the following telemetered data from the aircraft (Section VIII).

Performance:

- $\epsilon_{\dot{x}_h} \left(= \dot{x}_{h_c} - \hat{\dot{x}}_h\right)$ - heading-referenced longitudinal velocity error
- θ - pitch attitude
- $\epsilon_z \left(= z_{e_c} - \hat{z}_e\right)$ - altitude error
- $\epsilon_{\dot{Y}_h} \left(= \dot{Y}_{h_c} - \hat{\dot{Y}}_h\right)$ - heading-referenced lateral velocity error
- ϕ - bank attitude

Workload:

- ITVIC time delay - for manual duct rotation configurations, the length of time required for the pilot to respond to the duct rotation director light.
- δ_{es}, δ_{cs}, δ_{as} - evaluation pilot's longitudinal, collective, and lateral stick position inputs

The performance/workload data processing yielded means and standard deviations (μ and σ, respectively) from which the actual performance and workload measures were derived. Each measure is either the standard deviation of the individual parameter ($\sigma_{(\ )}$) or a quantity designated $|(\ \ )|_{max}$ which indicates the absolute value of the maximum of the quantity$(\mu_{(\ )} \pm 2\sigma_{(\ )})$. The rationale for these measures is discussed in Appendix VI. The performance/workload metrics correspond generally to those typically considered in measuring performance and workload; the data processing required to obtain them in a form suitable for ANOVA is discussed in Appendix VI. Somewhat atypical is the inclusion for analysis of the ITVIC time delay. Reference 51 suggests that "workload margin" be defined as the pilot's ability (or capacity) to accomplish additional (expected or unexpected) tasks; the time between the appearance of the duct rotation light and the actual duct rotation may be considered a measure of this quantity.

In general, performance and workload measures taken from flying qualities experiments may lead to erroneous conclusions because of the evaluation pilot's efforts in exploring the configuration being evaluated. For example, a "good" configuration may yield "poor" performance and "high" workload measures when compared to a "poor" configuration simply because the pilot is unwilling to allow significant errors to build up with the "poor" configuration but is perfectly willing to generate errors with the "good" configuration in order to perform a valid evaluation of the system. It was considered that, because of the relative difficulty of the evaluation task for this experiment, the evaluation pilot would in general attempt to achieve the best possible performance of the task; therefore it was believed that valid results could be derived from the performance and workload analyses for the deceleration element of the evaluation task if these results were carefully interpreted in the light of the flying qualities results.

The results of the ANOVA technique applied to the performance and workload measures are now discussed in the following subsections, following the framework summarized in Section 10.2.

10.4 MAJOR EFFECTS ON PERFORMANCE/WORKLOAD

In general, significant effects on all the performance and workload measures exist due both to control system complexity independent of display sophistication and to display sophistication independent of control system complexity at a 1% level of significance; the one exception is in glide slope tracking performance where the independent effect of variations in control system complexity is significant at only a 5% level. Recalling that no artificial stability augmentation was provided in the vertical axis for any of the control systems with the exception of the DVC system, this particular result is certainly reasonable.

- Control System Effects

In general, the rate augmentation (RATE) system yielded the poorest performance and highest workload of any of the control systems

investigated for the deceleration on the glide slope, while the decoupled velocity control (DVC) system yielded the best performance for the lowest pilot workload. Table 10-1 compares the mean performance and workload measures for these two systems as derived in Appendix VI.

Table 10-1

PERFORMANCE/WORKLOAD COMPARISONS FOR RATE AND DVC SYSTEMS

Control System \ Measure	$\lvert\epsilon_{\dot{x}_h}\rvert_{max}$ (ft/sec)	σ_θ (deg)	$\sigma_{\delta_{es}}$ (in)	$\lvert\epsilon_z\rvert_{max}$ (ft)	$\sigma_{\delta_{cs}}$ (deg)	$\lvert\epsilon_{\dot{Y}_h}\rvert_{max}$ (ft/sec)	$\lvert\phi\rvert_{max}$ (deg)	$\sigma_{\delta_{as}}$ (in)
RATE	20.1	3.2	0.91	32.8	2.48	11.5	5.2	0.24
DVC	8.9	2.0	0.34	24.3	1.32	8.9	4.5	0.21

In addition, the RATE system yielded a significantly larger maximum value of the ITVIC time delay (1.65 sec) than did the other manual duct rotation control systems.

These results support the flying qualities results which indicate that an inordinate amount of effort (both physical and mental) is necessary to perform both the stabilization and control functions required for the task with the RATE system, particularly in the lateral/directional degrees of freedom.

The attitude/rate augmentation system (ATT/RATE) in general yielded pilot-vehicle performance in the longitudinal degrees of freedom superior to that achieved by the attitude augmentation (ATT) and automatic duct rotation (AUTO) systems; this level of performance was attained with workload measures which were comparable to those obtained for the ATT and AUTO systems. The lateral tracking performance of the ATT/RATE system was comparable to that achieved by the ATT system and required smaller stick force inputs and bank angle excursions. This result tends to support the control system preferences of pilots reported in References 13 and 20 for the VTOL instrument approach, not including the final hover and landing.

The ATT and AUTO systems yielded comparable performance and workload levels in the longitudinal degrees of freedom; however, the lateral tracking performance with the AUTO system was significantly better than with the ATT system and comparable to that achieved with the DVC system. Furthermore the mean lateral stick force inputs and roll angle excursions of the ATT system were the largest of all the control systems investigated for this portion of the approach ($\sigma_{\delta_{as}}$ = 0.25 in and $\lvert\phi\rvert_{max}$ = 6.0 deg). The lateral tracking

results for the ATT and AUTO control systems provide an excellent example of the trade-off between performance and workload: reduction of the workload in one axis (duct rotation) permits increased pilot attention to performance in other axes (lateral tracking).

- Display Effects

The control director format (ED-3) yielded the best longitudinal velocity and glide slope tracking performance, but with the highest longitudinal and collective stick workloads, of the three most sophisticated formats for the glide slope deceleration portion of the task. The lateral performance and stick workload for this format, however, did not follow this trend; workload was lower and performance was worse than with the ED-2 format. The pilot's mental workload, as measured by the ITVIC time delay, was higher (longer time delay) for the director format than for either ED-2+ or ED-2. The effects of the ED-3 display on the longitudinal control problem are similar to those postulated in Reference 13 for "quickened" displays: improved performance through increased pilot effort devoted to vehicle stabilization; it is hypothesized that the degradation in lateral performance and decrease in the magnitude of the lateral stick force inputs with the ED-3 format reflect the pilot's concentration on the longitudinal control problem, in particular the control of vertical errors.

The velocity display formats (ED-2 and ED-2+) yielded poorer longitudinal velocity tracking performance but a lower workload than the ED-3 format. Comparable workloads and performance levels existed in the vertical degree of freedom for the ED-2+ and ED-3 displays, the same collective director display being included in both formats; however the ED-2 pursuit tracking display task for vertical errors yielded a significantly poorer performance (but a lower δ_{cs} workload) in that axis. The ED-2 format produced the largest lateral stick force inputs and roll angle excursions with the best lateral tracking performance of all three displays, possibly indicating a shift in the pilot's efforts from the longitudinal to the lateral control tasks.

Table 10-2 compares the mean performance and workload measures for these three display formats as derived in Appendix VI.

Table 10-2

PERFORMANCE/WORKLOAD COMPARISON
FOR VARIATIONS IN DISPLAYED INFORMATION

Measure / Display Format	$\lvert\epsilon_{\dot{X}_h}\rvert_{max}$ (ft/sec)	σ_θ (deg)	$\sigma_{\delta_{es}}$ (in)	$\lvert\epsilon_Z\rvert_{max}$ (ft)	$\sigma_{\delta_{cs}}$ (deg)	$\lvert\epsilon_{\dot{Y}_h}\rvert_{max}$ (ft/sec)	$\lvert\phi\rvert_{max}$ (deg)	$\sigma_{\delta_{as}}$ (in)	$\left(\begin{smallmatrix}ITVIC\\ \Delta t\end{smallmatrix}\right)_{max}$ (sec)
ED-3	11.5	2.3	0.56	27.8	1.99	11.0	4.9	0.22	1.52
ED-2+	17.2	1.9	0.43	14.5	1.92	9.9	5.1	0.21	1.20
ED-2	16.5	1.8	0.44	44.9	1.88	9.8	5.8	0.24	1.13

10.5 INTERACTIVE CONTROL/DISPLAY EFFECTS ON PERFORMANCE/WORKLOAD

From the model presented in Section 10.1, the combined control/display effects are the sum of the "major" control and display effects discussed in the preceding sub-section and the effects due to the interaction of a particular control system with a particular level of displayed information. Once again the discussion centers on the performance/workload measures from the deceleration on the glide slope with light turbulence and no significant crosswind; the effects of task, turbulence, and crosswind are discussed later in Section 10.6. The format is similar to that of the flying qualities section (Section IX) for a comparison of the results and the identification of any anomalies.

As was discussed in Section IX, the three general results apparent from Figure 9-1 are: (1) the demonstration of an inverse relationship between control complexity and display sophistication for constant pilot rating, (2) the need for explicit display of translational velocity information, and (3) the insensitivity of pilot rating to display details with the decoupled velocity control system. The relationships of the performance and workload measures with the pilot rating results may be observed by comparing them qualitatively for the configurations highlighted in Section IX. These comparisons are presented below; Appendix VI should be referred to for the quantitative measures.

Consider initially those three configurations just inside the PR = 3.5 contour in Figure 9-1: ATT/RATE:ED-3, ATT:ED-2+, and AUTO:ED-2. From the results of the analyses presented in Appendix VI, the ATT/RATE:ED-3 configuration yielded the best performance but highest workload of the three in the control of speed error while the AUTO:ED-2 configuration yielded the poorest performance but lowest workload. Laterally, ATT/RATE: ED-3 yielded a performance comparable to that of ATT:ED-2+ and an especially low workload level; both of these effects are caused in part by a control/display interaction: a roll rate command/attitude hold system and the lateral stick director. In contrast, AUTO:ED-2 produced the best lateral performance but highest lateral stick workload of the three; in the vertical degree of freedom, AUTO:ED-2 yielded the poorest performance and lowest collective stick workload. For these three pitch attitude-stabilized configurations, the display effects are dominant in the longitudinal degrees of freedom: the director display yields a higher but still satisfactory workload and enhanced performance while the velocity display yields a reduction in the efforts devoted to longitudinal control and a degraded, but still adequate, level of performance. Automatic configuration change appears to allow more concentration on the lateral tracking problem for the roll attitude-stabilized vehicle although pilot commentary indicates more concentration on glide slope control. A lateral control director produces adequate performance for the roll rate command/attitude hold system with an apparently low level of physical effort (lateral stick workload) although the overall mental effort required, as indicated by the ITVIC time delay, is high.

The lack of velocity status information on the display has significant effects on both the performance and workload measures. The most revealing disparity in performance between the ED-2 and ED-1 formats for the decelerating descent was in the vertical axis; although the control systems investigated were the AUTO and DVC systems, a mean maximum vertical error of ~82 ft occurred when vertical velocity was not explicitly displayed, as compared to a maximum error of ~37 ft with the velocity information. The DVC system tended to improve the vertical performance with a mean maximum error for DVC:ED-1 of ~41 ft, but the unaugmented vertical axis of the AUTO system led to a maximum error of 122 ft. From pilot commentary, the mental effort involved with the ED-1 format was severe:

DVC:ED-1 -- "Spent a lot of time looking at airspeed and rate of sink trying to correlate them with radar altimeter so that I could get some lead on the display. Really had to use peripheral instruments; it was difficult". (F-141)

Lacking explicit velocity information, ED-1 yielded a low longitudinal and lateral stick workload; however, the size of the collective inputs was significantly larger than that of the corresponding inputs for ED-2, thus further emphasizing the difficulties encountered in glide slope tracking with no integrated vertical velocity information.

With the addition of a separate three-axis control director (ED1/FD), the performance and workload measures for the ATT and RATE systems on the glide slope become comparable to the same measures for the ATT:ED-3 and RATE:ED-3 combinations respectively. However, according to the pilot evaluation data, the hover element of the task determined the crucial difference among these configurations.

Although, with velocity information provided, no trend in pilot rating with display sophistication was found to exist for the DVC system, significant performance and workload differences did occur. The display of control director information yielded better performance in the longitudinal degrees of freedom and a higher collective workload; for similar performance levels, the ED-3 format also yielded a higher lateral workload. It appears therefore that the overall reduction in mental and physical workload as a result of the "major" control system effect had a greater bearing on pilot rating than did the effect of variations in displayed information so long as velocity was explicitly included as part of that information.

Considering now the remainder of the configurations rated satisfactory (PR $\leq$ 3.5), the following performance/workload effects can be seen. The effect of adding pitch and roll control director information to the ATT:ED-2+ combination, i.e. ATT:ED-3, was an improvement in speed control at the expense of a higher, but according to the pilot rating, still satisfactory, longitudinal stick workload and an increase in lateral stick workload with no significant improvement in lateral performance. However, as will be discussed later, the

lateral control director appears to minimize the effects of turbulence on performance for the same workload level while the velocity display yields degraded lateral performance in turbulence for the same physical workload level. The performance/workload levels for the vertical axis remain the same; no difference in the vertical display exists between the two formats.

The effect of adding a collective director to the AUTO:ED-2 configuration (AUTO:ED-2+) is a significant improvement in glide slope tracking performance for a comparable collective workload; this improvement was accompanied by an increased longitudinal stick workload and improved speed control. The addition of the automatic configuration change feature (ATT:ED-2+ $\Rightarrow$ AUTO:ED-2+) produced smaller collective stick inputs for a similar level of vertical performance ("When I do the duct rotation collective control is not as precise" - F-131) and apparently allowed the pilot to concentrate on lateral tracking: larger lateral stick inputs were accompanied by improved lateral performance.

Consider now those configurations with $4 \leq PR \leq 6$ (<u>adequate</u> performance attainable with <u>increased</u> pilot workload up to the <u>maximum tolerable</u> level). The RATE system qualified for this category only with control director information displayed (RATE:ED-3) and small crosswind components. As is discussed in Section 10.4, the additive control and display effects could be expected to produce an extremely high and possibly unacceptable workload level for this combination; although relatively large values for all the workload measures did exist, significant interactive control/display effects acted counter to the major effects on physical workload in pitch and collective. This apparent reduction in workload came at the expense of the glide slope tracking performance which was found to be poorer than would have been predicted by the major effects alone. However, significant interactive effects which increased lateral workload above, and degraded the lateral performance below, the levels predicted by the major effects alone were also identified. No evidence of any workload approaching the "maximum tolerable" level was found in the pilot comments concerning the deceleration on the glide slope ("Glide slope and localizer tracking very easy task, ... flight director ... very natural. Deceleration profile no problem." - F-121). The problems with this configuration which most heavily influenced pilot rating occurred near the hover and are discussed later in this subsection.

The removal of the pitch and roll control directors from the ATT/RATE:ED-3 configuration (ATT/RATE:ED-2+) yielded an increased lateral workload for a comparable level of performance; this increase apparently came about at the expense of the pilot's speed control efforts (an interactive effect), as indicated by a relatively poor performance in that axis.

A further reduction in display sophistication (ATT/RATE:ED-2+ $\Longrightarrow$ ATT/RATE:ED-2) yielded a significant reduction in collective workload and a degradation in glide slope tracking performance. An increase in effort devoted to the longitudinal problem (shorter ITVIC time delay and higher pitch stick workload) was accompanied by improved performance in that axis. However an increase in lateral stick workload did not yield any significant improvement in localizer tracking performance.

The same reduction in display sophistication for the ATT system (ATT:ED-2+ $\Rightarrow$ ATT:ED-2) yielded an increase in collective workload and a dramatic degradation in glide slope tracking performance, both of which are attributed in part to significant interactive effects. ("Altitude control should be better; I have to devote too much time to it" - F-123). Significant interactive effects were also involved in the poor speed control and localizer tracking performance with the ED-2 display, apparently caused by the pilot's concentration on the altitude control problem.

Finally, those configurations for which adequate performance was not attainable with the maximum tolerable pilot workload ($7 \leq PR \leq 9$) were of two basic types: the one, previously discussed, consists of all the configurations in which velocity information is not explicitly displayed; the other is the RATE system in combination with any display format which does not include integrated pitch and roll control directors (RATE:ED-2+, RATE:ED-2). These two configurations actually yielded improved glide slope tracking performance through a significantly higher collective workload than was produced by the RATE:ED-3 combination; ED-2+ again yielded the better performance and higher workload of the velocity displays. However speed control was significantly poorer and pitch attitude excursions larger for similar pitch stick workloads. With light turbulence the velocity displays actually yielded better localizer tracking performance and a lower lateral stick workload; however roll attitude excursions were larger and, in turbulence, a large degradation in localizer tracking performance occurred with the velocity display while the director display tended to minimize this turbulence effect. These two configurations were down-rated only for the hover portion of the task; in light turbulence, the pilot had no major problems during the deceleration on the glide slope.

RATE:ED-2+ -- "Collective was good - easy to follow commands. .... keeping vector in diamond a bit difficult because wings get away. Felt the tracking was done pretty well." (F-130)

RATE:ED-2 -- "Easy (localizer and glide slope tracking), although occasionally have to cross-check ADI for bank angle. Deceleration profile no problem - can make nice smooth corrections and stop airplane where desired." (F-124)

10.6 COMBINED EFFECTS

- Task Effects

Similar performance measure analyses were also performed for the level deceleration to the hover in light turbulence (see Appendix VI). Recall from the flying qualities results of Section IX that all the RATE

systems were downgraded because of their characteristics at or near the hover. Table 10-3 presents a comparison of the mean performance measures achieved on the descending and level portions of the transition for the four rotational augmentation systems. The performance of the attitude-stabilized systems (ATT and AUTO) improved near the hover in all three translational degrees of freedom although larger pitch attitude excursions were required. When provided with the ATT/RATE system the pilot appears to have been concentrating his efforts on lateral stabilization and control near the hover and neglecting the longitudinal and vertical problems. During the level deceleration, the performance of the RATE system degraded significantly in all three translational degrees of freedom; moreover the pilot's increased difficulty in stabilization of the vehicle is demonstrated by the relatively large attitude excursions which occurred near the hover.

Table 10-3

EFFECTS OF FINAL DECELERATION ON PERFORMANCE

OF ROTATIONALLY-AUGMENTED SYSTEMS

Control System \ Perf. Measure		$\lvert \epsilon_{\dot{X}_h} \rvert_{max}$ (ft/sec)	$\lvert \theta \rvert_{max}$ (deg)	$\lvert \epsilon_Z \rvert_{max}$ (ft)	$\lvert \epsilon_{\dot{Y}_h} \rvert_{max}$ (ft/sec)	$\lvert \phi \rvert_{max}$ (deg)
RATE	(1)	20.1	6.4	32.8	11.5	5.2
	(2)	29.2	11.6	35.5	17.8	8.8
ATT/RATE	(1)	11.0	2.2	21.5	10.7	5.2
	(2)	18.1	7.5	28.4	8.4	6.1
ATT	(1)	18.2	3.3	35.1	10.6	6.0
	(2)	13.3	9.8	33.5	9.6	5.9
AUTO	(1)	17.1	3.7	31.6	9.7	5.5
	(2)	14.0	8.8	26.3	8.9	6.8

(1) Descending deceleration
(2) Final level deceleration

Table 10-4 presents a comparison of the display effects on the performance of the RATE system for the descending and level decelerations. With the ED-3 format, the pilot tended to neglect the pitch and roll control directors during the level deceleration in favor of his status display (orientation, position, and velocity), which resulted in large attitude excursions.

RATE:ED-3 -- "Problem with the heading and knowing which way to go. The director needles didn't seem to help. I look at the airplane symbol to drive up to the spot.

I am getting a lot of good information from the velocity vector, however, and using it could get to the spot and stopped." (F-108)

Recall that the velocity command diamond is not included on the ED-3 format; it is hypothesized that the longitudinal and lateral performance in the level deceleration degraded significantly as a result of its absence. However the pilot did not neglect the collective director as evidenced by the improved vertical performance near the hover.

The RATE:ED-2+ configuration yielded comparable performance for both elements of the task. However the increased magnitude of the pitch and roll excursions demonstrates the stability problems encountered near the hover.

When provided with the RATE:ED-2 combination, the pilot appears to have devoted his efforts to attitude stabilization and lateral control and neglected the longitudinal and vertical control problem.

RATE:ED-2 -- "(Hover) really a problem. Hard to get enough attitude information from electronic display. ... Scan to ADI for attitude information in hover created a problem in keeping over spot." (F-124)

Table 10-4

DISPLAY EFFECT ON PERFORMANCE FOR RATE SYSTEM

Display Format \ Perf. Measure		$\lvert \epsilon_{\dot{x}_h} \rvert_{max}$ (ft/sec)	$\lvert \theta \rvert_{max}$ (deg)	$\lvert \epsilon_z \rvert_{max}$ (ft)	$\lvert \epsilon_{\dot{Y}_h} \rvert_{max}$ (ft/sec)	$\lvert \phi \rvert_{max}$ (deg)
ED-3	(1)	13.5	5.1	43.9	14.6	4.9
	(2)	26.5	13.8	38.9	28.9	10.8
ED-2+	(1)	23.9	8.0	18.2	10.7	5.5
	(2)	24.4	14.2	21.0	14.2	10.1
ED-2	(1)	22.9	6.1	36.4	9.1	5.4
	(2)	36.9	7.0	46.8	10.4	5.6

(1) Descending deceleration
(2) Final level deceleration

According to the pilot evaluation data, without explicitly displayed velocity information, system performance was unacceptable during the final approach to the hover even with the most highly augmented controlled vehicles investigated (AUTO and DVC). Height-keeping performance with no artificial height damping (AUTO:ED-1) was particularly poor with large excursions about a mean altitude of ~65 ft AGL for the final portion of the two approaches.

AUTO:ED-1 -- "Glide slope tracking was pretty good up and away, but the commanded level off at 100 feet is impossible. You can't get enough information quickly enough there. I overshot dramatically and think we would have hit the ground". (F-124)

This situation was improved by the DVC:ED-1 configuration which yielded mean altitude errors of ~30 ft above the commanded 100 ft hover altitude. The difficulty with anticipating the level-off maneuver also resulted in speed control problems after that maneuver; a nose-down pitch attitude of ~7° which was acceptable for the descent was maintained in level flight with the AUTO:ED-1 system, resulting in final approach speeds ~15 Kts higher than desired and a large initial overshoot of the touchdown point. The DVC system improved the speed control performance but not to the point at which an acceptable precision hover could be attained.

- Turbulence Effects

As was discussed in Section 9.2.1, except for the RATE system, increased turbulence levels had minimal effect on pilot rating for a given configuration. The primary effect of the increased level of turbulence, as identified by pilot commentary, is the lateral velocity response of the aircraft as displayed to the pilot by his roll control director and/or velocity vector. In general, the control director format tended to "windproof" system performance while the velocity display yielded significantly degraded performance in turbulence both laterally and vertically.

Table 10-5 demonstrates the effects of turbulence on the ED-3 configurations during the descending deceleration. The RATE:ED-3 combination yielded slightly degraded lateral and vertical performance with smaller lateral and collective control inputs. The increased size of pitch stick inputs and more significantly degraded speed control were apparently caused by the lack of error limiting on the pitch director bar:

RATE:ED-3 -- "The problem is that you want to center the horizontal bar but it seems that you will then get large attitudes. I don't trust the horizontal bar to keep the attitude within its proper range -- have to go to attitude indicator to keep pitch attitude within limits and just let the horizontal bar drift off" (F-140).

The roll control director of the ATT/RATE:ED-3 combination appears to be more sensitive to turbulence than its RATE system counterpart. Larger lateral stick inputs and significantly degraded lateral tracking performance are the dominant turbulence effects; the improved vertical performance was apparently the result of a relaxation of effort in lateral control allowing more precise collective inputs.

> ATT/RATE:ED-3 -- "Glide slope tracking good. Localizer a problem because turbulence oscillates aircraft in roll and vertical bar quite sensitive. ...Tendency is to lag vertical bar to see if movement is caused by turbulence and therefore to get behind on localizer." (F-128).

The pitch and roll directors of the ATT:ED-3 configuration apparently wind-proofed longitudinal and lateral system performance. The significant degradation in glide slope tracking performance in turbulence is not reflected in the pilot evaluation data; it is hypothesized that the pilot had not reached the proficiency level for this early evaluation flight (F-120) that he achieved for the later evaluations of this configuration. In addition, recall that the sense of the altitude error diamond was different for these two evaluations; the "preferred" sense was implemented after flight F-121 (see Appendix V) and so was used for the light turbulence evaluation only with this configuration.

Table 10-5

TURBULENCE EFFECTS ON ED-3 CONFIGURATIONS

DURING DESCENDING DECELERATION

Measure / Config.		$\lvert\epsilon_{\dot{x}_h}\rvert_{max}$ (ft/sec)	σ_θ (deg)	$\sigma_{\delta_{es}}$ (in)	$\lvert\epsilon_z\rvert_{max}$ (ft)	$\sigma_{\delta_{cs}}$ (deg)	$\lvert\epsilon_{\dot{Y}_h}\rvert_{max}$ (ft/sec)	$\lvert\phi\rvert_{max}$ (deg)	$\sigma_{\delta_{as}}$ (in)	$\left(\frac{ITVIC}{\Delta t}\right)_{max}$ (sec)
RATE	(1)	13.5	2.6	0.90	43.9	2.29	14.6	4.9	0.28	1.82
	(2)	21.6	2.9	0.97	55.5	1.88	18.8	5.5	0.23	0.85
ATT/RATE	(1)	9.2	1.5	0.44	23.3	2.12	9.7	4.3	0.13	1.56
	(2)	14.4	1.2	0.25	10.4	1.55	17.2	5.0	0.17	1.19
ATT	(1)	9.4	2.4	0.55	16.6	1.96	10.7	6.2	0.25	1.19
	(2)	12.7	2.0	0.54	59.1	1.99	11.5	6.5	0.24	1.05

(1) Light Turbulence Effects
(2) Moderate Turbulence Effects

The increased lateral workload and significantly degraded lateral tracking performance in turbulence for all three control systems with the velocity display is demonstrated in Table 10-6. The increased difficulty of the pilot's lateral control problem is also manifested in other axes, primarily the vertical; the decreased size of the collective inputs and the degraded glide slope tracking indicate a concentration of effort on the control of the velocity vector through the center stick. Roll attitude stability problems were also encountered with the RATE and ATT/RATE systems as indicated by the increased magnitude of the roll excursions in turbulence.

RATE:ED-2+ -- "Electronic display a bit of a problem because using the stick alone to keep the velocity vector in the diamond leads to getting extreme attitudes: you have to do more than just move the stick ... got way behind on collective because I couldn't scrutinize electronic display closely enough since I had to concentrate on the (attitude indicator)" (F-132).

ATT/RATE:ED-2+ -- "(Tracking) some problem because turbulence seems to upset roll and so the diamond gets away from the end of the vector. ... The problem seems to be more the upsets than the (display) sensitivity. ... Result is a bit more of a problem tracking both localizer and glide slope" (F-128).

ATT:ED-2+ -- "(The display) seems more sensitive in turbulence because it does respond to turbulence and I try to keep up with that. Some problems caused by flying high gain on things that move around for reasons other than my inputs" (F-134).

A final general observation on the effects of turbulence concerns the ITVIC time delay. The time interval between a duct command light and the required duct rotation was smaller in turbulence; this effect is indicative of a tightening of the thrust vector control loop in turbulence which is especially evident with the "poor" control/display systems. The pilot was apparently aware that, if a tight duct angle control loop was not flown with these systems in turbulence, major degradations in overall system performance would occur.

Table 10-6

TURBULENCE EFFECTS ON ED-2+ CONFIGURATIONS

DURING DESCENDING DECELERATION

Measure / Config.	$\lvert\epsilon_{\dot{X}_h}\rvert_{max}$ (ft/sec)	σ_θ (deg)	$\sigma_{\delta_{es}}$ (in)	$\lvert\epsilon_z\rvert_{max}$ (ft)	$\sigma_{\delta_{cs}}$ (deg)	$\lvert\epsilon_{\dot{Y}_h}\rvert_{max}$ (ft/sec)	$\lvert\phi\rvert_{max}$ (deg)	$\sigma_{\delta_{as}}$ (in)	$\left(\frac{ITVIC}{\Delta t}\right)_{max}$ (sec)
RATE (1)	23.9	4.0	0.91	18.2	2.78	10.7	5.5	0.22	1.33
RATE (2)	23.9	3.7	0.70	34.3	1.73	25.5	8.9	0.30	0.96
ATT/RATE (1)	16.6	0.6	0.23	8.8	1.98	10.6	5.1	0.20	1.15
ATT/RATE (2)	15.4	1.0	0.27	22.3	1.78	32.3	7.0	0.22	1.05
ATT (1)	18.0	1.2	0.36	7.5	1.94	8.8	4.8	0.20	1.12
ATT (2)	11.5	0.8	0.11	52.1	1.59	28.9	5.5	0.23	1.06

(1) Light Turbulence Effects
(2) Moderate Turbulence Effects

- Crosswind Effects

The pilot's difficulties with the RATE systems in crosswind at or near the hover are exemplified not so much by the magnitudes of the individual errors but by their relationship to each other. For example, with the ATT:ED-3 system, the pilot was able to reduce the magnitudes of all the errors simultaneously by an increase in his effective gain:

ATT:ED-3 -- "Used flight director all the way. The harder I worked at it the closer I kept it and the better job I did. ..." (F-139).

In contrast, the hover element of the task in a crosswind with the RATE:ED-3 configuration was characterized by large altitude errors ($\sim$60-70 ft high) and horizontal velocity errors which were out of phase; that is, small longitudinal velocity errors were accompanied by large lateral velocity errors and vice versa. This effect apparently resulted from the heading problem with a crosswind and the pilot's previously discussed neglect of the pitch and roll control directors near the hover with the RATE system.

RATE:ED-3 -- "I cheat by staying high until I get the longitudinal and lateral problems solved, and then get down to the altitude I want." (F-140)

With the substitution of the velocity command diamond for the pitch and roll control directors (RATE:ED-2+), the vertical performance improved significantly. However the same out-of-phase relationship between the longitudinal and lateral velocity errors occurred:

RATE:ED-2+ -- "Biggest problem is control of bank attitude and heading. ... Velocity command is good unless I get way off in which case can't judge longitudinal corrections required if vector isn't in diamond" (F-130).

- No - ITVIC Effects

An investigation of the effects of a lack of a configuration change director on the performance/workload measures for the descending deceleration revealed no significant effects with one exception. With the ATT:ED-2 configuration, localizer tracking performance degraded significantly when no duct rotation director was present:

ATT:ED2 (No ITVIC) - "On second approach I got behind and it was difficult to figure out how to get back, particularly on localizer. ... When I got off on the localizer, so the vector didn't pass through the diamond, then I get ahead or behind on the duct rotation. It's easy only if you're right on the localizer so vector passes through the diamond.

Because of the absence of the ITVIC director light the major difficulty with the ATT:ED-3 (No ITVIC) configuration was not measured, i.e. the high mental workload required.

ATT:ED-3 (No ITVIC) - "The (control director) needles give good information, but having to use the horizontal needle as both a stick director and a duct change director to slow down is a very difficult mental process. ... Really have to use peripheral instruments, particularly duct angle and velocity." (F-123)

10.7 CONCLUDING REMARKS

Meaningful results of the analyses of performance/workload data are only possible if the experiment which generated the data was carefully designed. To wit, the use of a factorial design for the experimental matrix allowed the determination of significant control system, display, and control/display effects on the selected performance/workload measurements through statistical analysis of variance techniques. Moreover the use of the ground simulator as an experiment design tool resulted in a configuration matrix with wide variations in performance/workload characteristics, thus allowing a more valid evaluation of the trade-offs of system performance and pilot workload caused by control/display variations.

A difficulty which is not peculiar to this experiment is the measurement of pilot workload. The use of RMS levels of control usage as a physical workload metric neglects the importance of the frequency characteristics of the control input; small, high frequency control inputs may indicate a higher physical workload than large low frequency inputs and may also imply a high mental workload. Careful interpretation of the physical workload measures through the use of the pilot evaluation data was therefore essential for meaningful results.

Similarly the quantitative measure of mental workload used in this experiment, the ITVIC time delay, could have led to fallacious results had pilot evaluation data not been available. In light turbulence the time delay appears to be positively correlated with the mental workload, i.e. long time delays imply high mental workload. In higher turbulence levels however, the time delay is in general smaller and in particular is smaller for the high mental workload configurations (as identified by pilot evaluation data) than for the "good" configurations, indicating only the relative increase in the priority of the duct angle control task for the "poor" configurations.

Measures of pilot-vehicle performance and pilot workload are important insofar as they further quantify the performance/workload interactions and tradeoffs indicated by the assigned Cooper-Harper pilot rating. The results of this section demonstrate that this quantification process can only yield meaningful results when careful attention is paid to pilot commentary, elicited by a carefully thought out comment card, as an aid in the interpretation of the data. For example, without pilot evaluation data, the ATT/RATE:ED-2 configuration would have been rated significantly better than the ATT:ED-2 configuration based upon a comparison of each performance and workload measure. Both of these configurations were assigned pilot ratings of 4~5, roll control being the problem with the former and altitude control the difficulty with the latter. The basic problem is that the performance and workload measures give no indication of what performance, in the pilot's opinion, could have been achieved and only supply a measure of what actually was achieved. The pilot rating data however not only indicate that, in the pilot's opinion, adequate performance was attainable for both configurations with tolerable pilot compensation but also identify the element of his control task which required the increased workload.

Section XI

CONCLUSIONS

The experiment described in this report was performed using the X-22A variable stability, variable display V/STOL aircraft, which is capable of changing both stability/control characteristics and display presentations in flight. The guidance, display, and control system developments that were investigated are therefore largely independent of the actual aircraft employed. Some of the dynamic situations simulated were dependent on the basic aerodynamic characteristics of the X-22A; these characteristics are, however, representative of this class of vehicle.

General conclusions which may be drawn from the results of this flight program are:

- Descending decelerating approach transitions from forward flight to the hover may be performed by VTOL aircraft under instrument conditions given satisfactory control and display system characteristics as defined by this experiment.

- A trade-off between control augmentation complexity and display presentation sophistication exists for generic levels of each.

The pilot rating and comment data were obtained from one evaluation pilot in this experiment; these data lead to the following conclusions pertinent to the effects of the control system and display variables investigated in this experiment:

- Satisfactory task performance is achieved without pitch and roll control directors, for manual configuration changes, with the Independent Thrust Vector Inclination Command (ITVIC), if an attitude command system in pitch and roll and a dual-mode yaw command system is implemented. No effect of crosswinds on the ratings for this combination was observed.

- Pilot comments for all the control systems investigated express a preference for a control-force-aircraft-attitude relationship in both pitch and roll for instrument hover. This conclusion might be qualified by the fact that the attitude presentation on the electronic display apparently was difficult to interpret intuitively; nonetheless, the comments indicate a desire to obtain the attitude information through control forces rather than visual scanning.

- For VTOL aircraft like the X-22A with low natural height damping in and near the hover, a thrust magnitude director

is required for satisfactory task performance if the pilot must also perform configuration changes. Relieving the pilot of the configuration change task allows increased attention to the vertical tracking task and removes the requirement for a control director in that axis.

- The minimal level of displayed information must include translational velocity information to obtain acceptable performance, regardless of the level of control augmentation. This requirement is primarily hover-oriented, and reflects the pilot's dislike of having to obtain translational rates implicitly from the movement of symbols on the display.

- Rate augmentation alone is unacceptable for the task investigated unless full control director information is provided. Although performance with the rate system became unacceptable in crosswinds even with full director information, it is possible that an improved attitude presentation and the addition of wind direction information would provide an acceptable, although still unsatisfactory, system.

- Decoupling and augmenting the longitudinal and vertical velocity responses to control inputs considerably enhanced task performance, and tends to eliminate the trends of pilot rating with display sophistication in the configurations where ground velocity is explicitly displayed.

- The Independent Thrust Vector Inclination Command (ITVIC) director for manual configuration changes was required to achieve satisfactory system performance.

- A simple implementation of airspeed-groundspeed command and tracking switching was shown to be valuable as a means of maintaining aircraft parameters within the allowable transition corridor.

The analysis of system performance and pilot workload in terms of tracking errors and control usage measures, respectively, showed significant effects due not only to independent variations in control system complexity and display sophistication but also to interactive contributions of various combinations. These effects may be summarized as:

- Control System Effects

  (1) Improvements in system performance and reductions in pilot workload generally occurred with increasing levels of control system augmentation and automation for both the descending and level deceleration portions of the task.

(2) The primary effect of providing automatic duct rotation was to improve lateral tracking performance.

- Display Effects

  (1) Increases in display sophistication for the vertical information yielded significant improvements in vertical tracking performance at the expense of increased collective stick workload.

  (2) The longitudinal velocity tracking was significantly better with the control director format (ED-3) than with the velocity command formats (ED-2+, ED-2) at the expense of significantly higher longitudinal stick workload.

- Combined Effects

  (1) The performance/workload trade-offs implied by the Cooper-Harper pilot rating data were generally substantiated by the results of the performance/workload analyses.

  (2) Among those configurations receiving a pilot rating of $PR < 3.5$ (desired performance attainable with satisfactory workload), increased pilot workload levels (larger control usage measures) were accompanied by improved performance measures.

  (3) Comparing those configurations receiving a pilot rating of $3.5 < PR < 6.5$ (adequate performance attainable with tolerable workload) with those rated satisfactory ($PR < 3.5$), increases in pilot workload levels were evident and either similar or worse performance measures were obtained.

  (4) Those configurations receiving a pilot rating of $PR > 6.5$ (adequate performance not attainable with maximum tolerable workload) exhibited high workload levels and performance measures significantly worse than those configurations rated adequate ($PR < 6.5$).

The pilot-in-the-loop analysis was conducted to provide additional insight into the pilot rating results and to attempt to determine initial guidelines for control-display system designs. The following implications result from the analyses:

- A simple analysis procedure which determines the achievable closed-loop performance (in terms of bandwidth) for primary outer control loops assuming little or no pilot compensation corroborated major trends of the pilot rating data.

- For control/display configurations which provided neither attitude command augmentation nor control director information, an inner loop attitude closure by the pilot model was required to achieve outer-loop bandwidths comparable to the attitude command (ATT) system.

- For the task considered in this experiment, which includes instrument hover, it appears that a satisfactory bandwidth for the primary longitudinal and lateral velocity control loops is on the order of 1.0 rad/sec. Although this bandwidth can be achieved with the rate augmentation (RATE) and pitch-attitude/roll-rate command (ATT/RATE) systems by an inner-loop closure on attitude when control directors are not on the display (ED-2+, ED-2), for this experiment this inner-loop closure appears to be considered an unsatisfactory level of pilot compensation; it is possible, however, that an improved attitude presentation on the electronic display would alleviate the pilot's difficulties in this regard.

- It appears that a bandwidth of greater than 2.0 rad/sec is required for the primary altitude control loop with no inner loop altitude rate compensation if the pilot's control tasks include configuration changes, which implies a necessity for a quickened or director display in this channel for VTOL aircraft with low inherent height damping. If increased concentration on the vertical control problem is possible (e.g. automatic duct rotation plus "good" characteristics in the other channels), then an altitude control bandwidth of approximately 1.5 rad/sec can be achieved with inner-loop altitude rate error compensation, which appears satisfactory.

Section XII

RECOMMENDATIONS

12.1 IMPLICATIONS OF EXPERIMENT RESULTS FOR OTHER VTOL AIRCRAFT

The results from this experiment imply guidelines for the development of control systems and display presentations for other VTOL aircraft subject to the following qualifying remarks:

- The task considered required following a precise deceleration profile all the way to a hover, completely on instruments. Tasks which allow a breakout to visual conditions at some point (even if only for hover) or do not require precise deceleration tracking would probably result in relaxed control-display requirements.

- The intent of the control system variations investigated was to examine generic types of augmentation; hence, the response characteristics as implemented were generally "good" in the sense of compliance with MIL-F-83300. There is no guarantee, for example, that an attitude command system with lower natural frequencies and/or dampings or which includes significant control system dynamics such as lags, would be satisfactory with the same level of displayed information found suitable in this experiment.

- As was discussed in Section IX, the lack of displayed wind direction information may be responsible for the degradation of pilot rating in crosswind conditions when the control system did not include turn-following directional augmentation. It is possible that some display improvements -- including wind direction, improved attitude information, and perhaps additional integrated digital readouts -- would modify the results obtained with the RATE system in crosswinds. It is also noted, however, that the majority of the evaluations were conducted in low atmospheric turbulence; higher turbulence levels would be expected to degrade pilot ratings of the RATE system.

Keeping these considerations in mind, it is nonetheless possible to infer from the results of this experiment general guidelines necessary to achieve an instrument transition capability for other classes of aircraft.

For example, the CL-84 (Reference 16) is representative of a class which rotates aerodynamic surfaces in addition to thrust angle to transition from forward flight, while the AV-8A (similar to the Kestrel, Reference 21) is representative of jet-lift VTOL aircraft which can change thrust angle

rapidly and independently of aerodynamic surfaces. The stability augmentation systems of both aircraft consist of rate damping in pitch, roll, and yaw, with the CL-84 also including a low level of attitude augmentation in pitch; in general, the lower authority SAS used in the AV-8A results in less overall damping and hence slower responses than in the CL-84. For the AV-8A, the results of this experiment indicate that pitch and roll stick control directors on the display would be required to provide an adequate instrument transition capability; it is possible that the "instantaneous" thrust angle rotation from horizontal to vertical possible with the AV-8A, which provides the dual benefits of relieving the pilot of continuous thrust angle control and of providing a direct-lift control for glide path tracking , would allow satisfactory performance displaying only altitude and altitude rate errors rather than a power director. For the CL-84, it is possible that a good display of attitude would allow excluding pitch and roll stick directors (the RAE format used in the CL-84 experiments did not have them), depending on the actual characteristics of the control system, but the system would be unsatisfactory unless a throttle position director was added to the display and/or the wing tilt function was made automatic. As was discussed in Reference 16, the RAE format did not in fact include a power director, and the vertical control was unsatisfactory as would have been predicted by the X-22A results.

In general, therefore, the following guidelines for future VTOL control-display designs are implied by the results of this experiment:

- Explicit display of translational velocities is required regardless of control augmentation.

- A reduction in the dimensions of the pilot's control problem (nominally five controllers: pitch, roll, yaw, thrust magnitude, thrust angle) is probably necessary for a satisfactory system. As a minimum, directional augmentation (similar to that considered in this experiment for all the control systems except rate augmentation) appears desirable, particularly if the pilot must perform continuous control of thrust angle.

- If the pilot must perform continuous control of thrust angle a separate director display, such as the ITVIC, is desirable.

- The use of rate-augmentation-only control systems should be eschewed if an instrument hover capability with satisfactory pilot acceptance is required. An adequate instrument transition capability can be achieved with such systems if control directors are included in the display, however.

12.2 RECOMMENDATIONS FOR FUTURE RESEARCH

Based on this experiment, further research of control and display requirements for VTOL instrument approaches and landing is recommended as follows:

1. The influence of the task on the control-display requirements should be ascertained. In particular, the effect of breakout to visual conditions at various altitudes and/or ranges should be investigated, as should different deceleration profiles.

2. The required dynamic characteristics of the generic control system types investigated in this experiment should be defined and correlated with the MIL-F-83300 requirements. Of direct interest are time constants, frequencies, damping ratios, and lags or input delays for the rotational augmentation; in addition, system implementations which use a deadband in the rate-command signal, or which provide attitude command for small inputs and rate command for large inputs should be explored.

3. The influence of an improved attitude presentation and the addition of wind direction information on the electronic display should be determined for rate augmentation and rate-command-attitude-hold systems.

4. Improvements to the airspeed/ground speed switching logic to account for shears and tailwinds should be designed.

5. The pilot-in-the-loop analysis procedure initiated in this report should be extended and applied to additional data.

APPENDIX I

MASTER DATA SUMMARY

The appendices to this report contain background information and supporting data relevant to the Technical Discussion and Results presented in Volume I. This appendix (I) is contained in both volumes, and summarizes the most pertinent data for ready reference; the contents of the remaining appendices (Volume II) are listed below:

Appendix II:	Frequency responses of all control systems, selected time history responses to step inputs.
Appendix III:	Summary of the ground simulation investigations used in the experiment design.
Appendix IV:	Documentation of digital identification used to estimate achieved dynamic characteristics from flight data.
Appendix V:	Complete documentation of pilot comments for each evaluation.
Appendix VI:	Documentation of performance and workload analyses.
Appendix VII:	Documentation of estimation of winds and turbulence.
Appendix VIII:	Description of equipment.

Table I-1 is the master summary, listed according to control system, of all the evaluations performed in this experiment. The classification of the evaluations into primary (P), crosswind (CW), and NO-ITVIC (NI) matrices is given in the table. For the performance analyses given in Section X, a separation according to turbulence level is also made on the basis of turbulence effect rating (TER); as can be seen from the table, a TER of A through C generally corresponds to a turbulence level index of ≤ 3.2 ft/sec. The table also gives values of headwind and crosswind components estimated from aircraft measurements of airspeed and ground speed; in general, the values are biased relative to the winds called out by the airport tower during each evaluation (which are also included in the table) but do indicate in general the existing conditions. The estimation of wind and turbulence levels is discussed in Appendix VIII.

Table I-2 summarizes the longitudinal and lateral-directional stability and control derivatives in aircraft body axes at three flight conditions. These values are obtained by a digital identification technique from flight data; this procedure is discussed in Appendix IV. It is noted that the deriva-

TABLE I-1

MASTER DATA SUMMARY

CONTROL AUG.	ED FORMAT	ITVIC	ADI NEEDLES	DUCT ROTATION	PILOT RATING	FLIGHT NUMBER	MEASURED WINDS (FPS): HEADWIND†	CROSSWIND‡	TURBULENCE	TOWER WIND DIR./KTS	SPN-42 COURSE	EVAL. MATRIX
RATE	ED3	ON	OFF	MAN	4B	F-108	25.0	4.4(R)*	—	210°/15	220°	P
	ED3	ON	OFF	MAN	4C	F-121	17.6*	10.1(L)*	2.8	270°/12	300°	P
	ED3	ON	OFF	MAN	7B	F-130	-9.9	10.8(R)	2.3	010°/10	300°	CW
	ED3	ON	OFF	MAN	7C	F-140	-4.5	6.9(R)	3.2	350°/13	300°	CW
	ED2+	ON	OFF	MAN	7A	F-130	-5.6	11.8(R)	2.6	360°/08	300°	CW
	ED2+	ON	OFF	MAN	8E	F-132	19.0	6.0(R)	3.4	290°/20	255°	P
	ED2+	ON	OFF	MAN	8-1/2F	F-134	21.3	1.8(L)	3.6	230°/15	255°	P
	ED2	ON	OFF	MAN	7A	F-124	16.0*	7.6(R)	2.0	250°/11	220°	P
	ED1	ON	FD	MAN	7-1/2B	F-130	-9.4	14.0(R)	2.7	360°/05	300°	CW
ATT/RATE	ED3	ON	OFF	MAN	3D	F-128	22.4	13.2(L)	3.3	250°/15	280°	P
	ED3ˣ	ON	OFF	MAN	6B	F-133	7.8	3.9(L)	2.2	250°/15	280°	P
	ED3	ON	OFF	MAN	3C	F-142	0.0	8.7(R)	3.2	330°/09	300°	P
	ED2+	ON	OFF	MAN	4D	F-128	15.5	9.2(L)	3.3	250°/15	280°	P
	ED2+	ON	OFF	MAN	4D	F-132	22.5	7.7(R)	4.1	270°/20	255°	P
	ED2	ON	OFF	MAN	5D	F-127	25.0	4.4(R)*	—	270°/15	280°	P
	ED2	ON	OFF	MAN	4-1/2B	F-133	9.3	6.5(L)	1.9	250°/15	280°	P
ATTITUDE	ED3	ON	OFF	MAN	3D	F-120	25.4*	9.2(R)*	3.7	320°/16	300°	P
	ED3	ON	OFF	MAN	2A	F-131	3.5	3.6(L)	2.5	200°/08	220°	P
	ED3	ON	OFF	MAN	3D	F-139	-6.3	12.5(R)	3.3	010°/07	300°	CW
	ED2+	ON	OFF	MAN	3A	F-131	11.0	4.7(L)	2.0	210°/10	220°	P
	ED2+	ON	OFF	MAN	3E	F-134	24.8	9.1(L)	4.0	250°/15	255°	P
	ED2+	ON	OFF	MAN	2-1/2C	F-140	4.2	13.6(R)	3.2	360°/10	300°	CW
	ED2	ON	OFF	MAN	5D	F-121	17.6*	10.1(L)*	3.4	270°/12	300°	P
	ED2	ON	OFF	MAN	4B	F-123	6.5*	5.4(L)*	2.4	180°/05	220°	P
	ED1	ON	FD	MAN	7D	F-121	17.6*	10.1(L)*	4.0	270°/12	300°	P
	ED3	OFF	OFF	MAN	6D	F-123	7.6*	9.1(R)	3.0	230°/08	220°	NI
	ED2	OFF	OFF	MAN	6C	F-128	19.0	11.2(L)	3.0	250°/15	280°	NI
AUTO λ	ED3	ON	OFF	AUTO	2B	F-126	22.0	12.7(R)*	—	250°/15	280°	P
	ED2+	ON	OFF	AUTO	2A	F-131	10.9	0.5(L)	2.3	210°/10	220°	P
	ED2+	ON	OFF	AUTO	3D	F-134	22.0	4.6(L)	3.5	250°/15	255°	P
	ED2	ON	OFF	AUTO	3C	F-123	13.3*	2.3(R)*	3.0	230°/08	220°	P
	ED2	ON	OFF	AUTO	2-1/2A	F-133	9.4	5.0(L)	2.0	250°/15	280°	P
	ED1	ON	OFF	AUTO	7B	F-124	16.0*	11.8(R)	2.8	250°/11	220°	P
DVC	ED3	ON	OFF	AUTO	2C	F-142	0.0	12.5(R)	3.0	330°/09	300°	P
	ED2+	ON	OFF	AUTO	2C	F-142	0.0	10.9(R)	3.6	330°/09	300°	P
	ED2	ON	OFF	AUTO	2B	F-141	12.7	7.6(R)	2.6	340°/15	300°	P
	ED2	ON	OFF	AUTO	2B	F-141	11.4	9.7(R)	2.7	340°/15	300°	P
	ED1	ON	OFF	AUTO	7B	F-141	15.2	12.7(R)	2.3	340°/15	300°	P

†NEGATIVE SIGN INDICATES TAILWIND
‡LETTER INDICATES DIRECTION AS SEEN FROM AIRCRAFT
*MEASURED VALUES INVALID, TOWER VALUES RESOLVED
ˣDIFFERENT VBAR GAIN, NOT INCLUDED IN ANALYSES

TABLE I-2

BASIC AIRCRAFT STABILITY DERIVATIVES

		λ = 90 deg (0 Kt)	λ = 50 deg (65 Kt)	λ = 15 deg (100 Kt)
X_u	(1/sec)	-0.15	-0.18	-0.19
X_w	(1/sec)	0.0	-0.030	0.087
$X_{\delta_{es}}$	(ft/sec^2/in)	-0.143	-0.356	0.147
$X_{\delta_{cs}}$	(ft/sec^2/deg)	0.0	0.52	1.12
Z_u	(1/sec)	0.0	-0.20	-0.26
Z_w	(1/sec)	-0.12	-0.55	-0.65
$Z_{\delta_{es}}$	(ft/sec^2/in)	-0.16	0.0	0.61
$Z_{\delta_{cs}}$	(ft/sec^2/deg)	-1.50	-1.00	-0.36
M_u	(rad/ft-sec)	0.015	-0.010	-0.0066
M_w	(rad/ft-sec)	0.000875	-0.0177	-0.0049
M_q	(1/sec)	0.23	-0.09	-0.5
$M_{\delta_{es}}$	(rad/sec^2/in)	0.348	0.33	0.30
$M_{\delta_{cs}}$	(rad/sec^2/deg)	0.0	0.021	0.037
Y_v	(1/sec)	-0.060	-0.267	-0.30
Y_p	(ft/rad-sec)	1.67	0.573	0.347
Y_r	(ft/rad-sec)	-1.68	-0.108	-1.49
L'_v	(rad/ft-sec)	-0.015	-0.037	-0.0386
L'_p	(1/sec)	+0.07	-0.75	-1.05
L'_r	(1/sec)	0.0	1.24	1.85
$L'_{\delta_{as}}$	(rad/sec^2/in)	0.40	0.382	0.398
$L'_{\delta_{rp}}$	(rad/sec^2/in)	0.095	-0.150	-0.102
N'_v	(rad/ft-sec)	0.0011	0.001	-0.00118
N'_p	(1/sec)	0.0	-0.110	-0.178
N'_r	(1/sec)	-0.17	-0.21	-0.10
$N'_{\delta_{as}}$	(rad/sec^2/in)	0.043	0.052	0.068
$N'_{\delta_{rp}}$	(rad/sec^2/in)	0.23	0.15	0.058

tive estimates are all obtained for steady flight; the unsteady effects caused by the decelerating transition are therefore not included in the values for λ =50° (65 kt), and these values should therefore be interpreted as useful primarily to indicate the trends in the derivatives and modal characteristics.

A complete listing of all the transfer functions for the five control augmentation systems investigated is given in Table I-3. These modal characteristics were calculated using the basic aircraft derivatives listed in Table I-2 and the feedback-feed forward gains given in Section V. The pitch, roll, and/or yaw prefilters, as appropriate, are indicated by enclosing the aircraft transfer functions for those cases in brackets ({ }). The format used is as follows:

$$K\left(s+\frac{1}{\tau_1}\right)\left(s^2+2\zeta\omega_n s+\omega_n^2\right) \Longrightarrow K\left(\frac{1}{\tau_1}\right)\left[\zeta;\ \omega_n\right]$$

Finally, Tables I-4 and I-5 summarize the electronic display symbol sensitivities and control director gains (in terms of full scale values), respectively; these tables are a compilation of the information presented in Section VI.

TABLE I-3a

TRANSFER FUNCTIONS--RATE
AUGMENTATION CONTROL SYSTEM

	λ = 90 deg (0 kt)	λ = 50 deg (65 kt)	λ = 15 deg (100 kt)
LONGITUDINAL			
$\Delta(s)$	(.12)(2.94) [.10;.405]	(.18)(-.092) [.94;1.95]	(.93)(2.89)(.31)(-.12)
$N^{u}_{\delta_{es}}$	-.18(.12) [-.012;8.84]	-.447(.48) [.03; 5.86]	.185(-69.08) [.73;.78]
$N^{w}_{\delta_{es}}$	-.201(.78) [-.53;.79]	41.54 [.38;.25]	.766(+83.55) [.52;.20]
$N^{\theta}_{\delta_{es}}$	.437(.12)(.14)	.414(.17)(.58)	.377(.24)(.58)
$N^{u}_{\delta_{cs}}$	-.0021(-25.33)	.65(1.63)(2.56)(.43)	1.4(-.33) [.96;1.53]
$N^{w}_{\delta_{cs}}$	-1.875(2.94) [.10;.405]	-1.25(-.30) [.62;1.22]	-.45(-12.35) [-.35;.29]
$N^{\theta}_{\delta_{cs}}$	-.00164(.15)	.0263(.16)(1.17)	.046(.12)(.565)
LATERAL-DIRECTIONAL			
$\Delta(s)$	(1.62)(2.71) [-.025;.45]	(.73)(3.04) [.59;.81]	(.14)(3.14) [.42;1.35]
$N^{v}_{\delta_{as}}$	.60(1.72)(21.8)	-4.87(-3.85)(1.07)	2.1(.51)(12.13)
$N^{\phi}_{\delta_{as}}$	.403(.063)(1.74)	.388 [.92;1.02]	.4 [.59;1.10]
$N^{\psi}_{\delta_{as}}$	$\frac{.043}{(0)}$ (.90) [-.50;.95]	$\frac{.052}{(0)}$ (1.18) [-.46;1.10]	$\frac{.0685}{(0)}$ (.73) [-.17;1.18]
$N^{v}_{\delta_{rp}}$	-.278(-9.50)(.0045)	-18.69(-.091)(3.97)	-54.8(.072)(4.1)
$N^{\phi}_{\delta_{rp}}$	.116 [.126;.25]	-.183(-2.47)(1.60)	-1.24(-.41)(1.12)
N^{ψ}_{rp}	$\frac{.281}{(0)}$ (2.39) [-.02;.46]	$\frac{.183}{(0)}$ (3.69) [.17;.56]	$\frac{.071}{(0)}$ (1.4)(.22)

TABLE I-3b

TRANSFER FUNCTIONS--PITCH ATTITUDE/ ROLL RATE COMMAND CONTROL SYSTEM

	λ = 90 deg (0 kt)	λ = 50 deg (65 kt)	λ = 15 deg (100 kt)
	LONGITUDINAL		
$\Delta(s)$	(.12)(.17) [.74;4.29]	(.16)(.50) [.72;4.45]	(.23)(.55) [.76;4.1]
$N^{u}_{\delta_{es}}$	$\frac{[.7;4.0]}{[.7;2.0]}\left\{-.18(.12)\ [-.012;8.84]\right\}$	$\frac{[.7;4.0]}{[.7;2.0]}\left\{-.447(.48)\ [.03;5.86]\right\}$	$\frac{[.7;4.0]}{[.7;2.0]}\left\{.185(-69.06)\ [.73;.78]\right\}$
$N^{w}_{\delta_{es}}$	$\frac{[.7;4.0]}{[.7;2.0]}\left\{-.201(.78)\ [-.53;.79]\right\}$	$\frac{[.7;4.0]}{[.7;2.0]}\left\{41.54\ [.38;.25]\right\}$	$\frac{[.7;4.0]}{[.7;2.0]}\left\{.766(83.55)\ [.52;.20]\right\}$
$N^{\theta}_{\delta_{es}}$	$\frac{[.7;4.0]}{[.7;2.0]}\left\{.437(.12)(.14)\right\}$	$\frac{[.7;4.0]}{[.7;2.0]}\left\{.414(.17)(.58)\right\}$	$\frac{[.7;4.0]}{[.7;2.0]}\left\{.377(.24)(.58)\right\}$
$N^{u}_{\delta_{cs}}$	-.0044(-9.14)	.65(.51) [.76;4.41]	1.4(.54) [.63;4.02]
$N^{w}_{\delta_{cs}}$	-1.875(.17) [.74;4.29]	-1.25(.26) [.49;4.30]	-.45(.49) [.87;5.43]
$N^{\theta}_{\delta_{cs}}$	-.00164(.15)	.0263(.16)(1.17)	.046(.12)(.565)
	LATERAL-DIRECTIONAL*		
$\Delta(s)$	(.17)(1.67)(2.60) [.52;2.15]	(.48) [.48;2.38] [.97;1.70]	(.52) [.44;2.53] [.83;1.49]
$N^{v}_{\delta_{as}}$	$\frac{(2)}{(0)}\left\{.60(22.19)\ [1.0;1.96]\right\}$	$\frac{(2)}{(0)}\left\{-5.07(1.83)(-4.10)(.062)\right\}$	$\frac{(2)}{(0)}\left\{2.13(14.71)(.11)(.75)\right\}$
$N^{\phi}_{\delta_{as}}$	$\frac{(2)}{(0)}\left\{.403(1.83)(2.16)(.060)\right\}$	$\frac{(2)}{(0)}\left\{.385(.73)\ [.89;1.48]\right\}$	$\frac{(2)}{(0)}\left\{.401(.55)\ [.51;1.61]\right\}$
$N^{\psi}_{\delta_{as}}$	$\frac{(2)}{(0)}\left\{.043(.92)\ [-.49;.94]\right\}$	$\frac{(2)}{(0)}\left\{\frac{.052}{(0)}(.50)(1.95)[-.46;1.90]\right\}$	$\frac{(2)}{(0)}\left\{\frac{.068}{(0)}(.50)(.82)\ [-.14;1.91]\right\}$
$N^{v}_{\delta_{rp}}$	$\frac{(1)}{(0)}\left\{-1.04(-.71)(-8.89)(0)\right\}$	-28.67(.50) [.83;2.31]	-24.39(.50) [.78;2.19]
$N^{\phi}_{\delta_{rp}}$	$\frac{(1)}{(0)}\left\{.433(0)\ [.43;.27]\right\}$	-.273(1.66)(-2.42)(.50)	-.186(.50)(1.76)(-2.41)
$N^{\psi}_{\delta_{rp}}$	$\frac{(1)}{(0)}\left\{1.05(.165)\ [.51;2.20]\right\}$	$\frac{.273}{(0)}$ (.50)(.55) [.75;2.22]	$\frac{.11}{(0)}$ (.50)(.44) [.81;2.77]

*ATC FOR λ = 15°,50°;HH FOR λ = 90°

TABLE I-3c

TRANSFER FUNCTIONS--ATTITUDE COMMAND AND AUTOMATIC λ CONTROL SYSTEMS

	λ = 90 deg (0 kt)	λ = 50 deg (65 kt)	λ = 15 deg (100 kt)
LONGITUDINAL			
$\Delta(s)$	(.12)(.17) [.74;4.29]	(.16)(.50) [.72;4.45]	(.23)(.55) [.76;4.1]
$N^{u}_{\delta_{es}}$	$\left\{\frac{[.7;4.0]}{[.7;2.0]}\right\}$ -.18(.12) [-.012;8.84] $\left\{\right\}$	$\left\{\frac{[.7;4.0]}{[.7;2.0]}\right\}$ -.447(.48) [.03;5.86] $\left\{\right\}$	$\left\{\frac{[.7;4.0]}{[.7;2.0]}\right\}$ .185(-69.06) [.73;.78] $\left\{\right\}$
$N^{w}_{\delta_{es}}$	$\left\{\frac{[.7;4.0]}{[.7;2.0]}\right\}$ -.201(.78) [-.53;.79] $\left\{\right\}$	$\left\{\frac{[.7;4.0]}{[.7;2.0]}\right\}$ 41.54 [.38;.25] $\left\{\right\}$	$\left\{\frac{[.7;4.0]}{[.7;2.0]}\right\}$ .766(83.55) [.52;.20] $\left\{\right\}$
$N^{\theta}_{\delta_{es}}$	$\left\{\frac{[.7;4.0]}{[.7;2.0]}\right\}$ .437(.12)(.14) $\left\{\right\}$	$\left\{\frac{[.7;4.0]}{[.7;2.0]}\right\}$ .414(.17)(.58) $\left\{\right\}$	$\left\{\frac{[.7;4.0]}{[.7;2.0]}\right\}$ .377(.24)(.58) $\left\{\right\}$
$N^{u}_{\delta_{cs}}$	-.0044(-9.14)	.65(.51) [.76;4.41]	1.4(.54) [.63;4.02]
$N^{w}_{\delta_{cs}}$	-1.875(.17) [.74;4.29]	-1.25(.26) [.49;4.30]	-.45(.49) [.87;5.43]
$N^{\theta}_{\delta_{cs}}$	-.00164(.15)	.0263(.16)(1.17)	.046(.12)(.565)
LATERAL-DIRECTIONAL*			
$\Delta(s)$	(.16)(1.70)(2.48) [.30;2.20]	(.49) [.31;2.44] [.96;1.63]	(.52) [30;2.66] [.74;1.41]
$N^{v}_{\delta_{as}}$	1.45(22.19) [1.0;1.96]	-12.2(-4.1)(1.83)(.062)	5.14(14.71)(.11)(.75)
$N^{\phi}_{\delta_{as}}$	.97(1.83)(2.16)(.060)	.928(.73) [.89;1.48]	.967(.55) [.51;1.61]
$N^{\psi}_{\delta_{as}}$	.104(.92) [-.49;.94]	$\frac{.126}{(0)}$ (.50)(1.95) [-.46;1.90]	$\frac{.165}{(0)}$ (.50)(.82) [-.14;1.91]
$N^{v}_{\delta_{rp}}$	$\left\{\frac{(1)}{(0)}\right\}\left\{ -1.04(-.59)(-10.6)(0) \right\}$	-28.67(.50) [.60;2.31]	-24.4(.50) [.56;2.19]
$N^{\phi}_{\delta_{rp}}$	$\left\{\frac{(1)}{(0)}\right\}\left\{ .433(0) [.43;.27] \right\}$	-.273(1.66)(-2.42)(.50)	-.186(.50)(1.76)(-2.41)
$N^{\psi}_{\delta_{rp}}$	$\left\{\frac{(1)}{(0)}\right\}\left\{ 1.05(.16) [.29;2.22] \right\}$	$\frac{.273}{(0)}$ (.50)(.51) [.49;2.30]	$\frac{.106}{(0)}$ (.50)(.43) [.57;2.80]

*ATC FOR λ = 15°, 50°, HH FOR λ = 90°

TABLE I-3d

TRANSFER FUNCTIONS--DECOUPLED VELOCITY CONTROL SYSTEM

	λ = 90 deg (0 kt)	λ = 50 deg (65 kt)	λ = 15 deg (100 kt)
LONGITUDINAL			
$\Delta(s)$	[.90;3.54] [.96;.58]	(1.45)(.43) [.86;3.42]	(2.04)(.83) [.88;2.47]
$N^{\dot{x}}_{\delta_{es}}$	.82(.90) [-.013;8.85]	2.04(1.30) [.07;6.38]	-.84(-8.84) [.93;4.40]
$N^{\dot{h}}_{\delta_{es}}$	.92(4.13)(-10.99)(-.033)	-4.27(-18.16)(.091)	-3.50(-6.29)(7.25)(.21)
$N^{\theta}_{\delta_{es}}$	1.99(.14)(.90)	1.89(1.03)(.27)	1.72 [.93;.61]
$N^{\dot{x}}_{\delta_{cs}}$	-.092 [-.018;8.9]	-.57(-1.66)(1.20)(13.30)	-3.00(-1.25) [.92;3.63]
$N^{\dot{h}}_{\delta_{cs}}$	3.39(.386) [.89;3.45]	2.26(.349) [.57;5.07]	-1.14(-12.16)(8.09)(.38)
$N^{\theta}_{\delta_{cs}}$	-.227(.14)	.61(.32)(.88)	1.04 [.95;.62]
$N^{\dot{x}}_{\dot{\lambda}}$	$\frac{2.44}{(0)}$ (.89) [.73;4.12]	$\frac{4.18}{(0)}$ (1.33) [.70;4.06]	$\frac{2.09}{(0)}$ (4.02) [.78;3.58]
$N^{\dot{h}}_{\dot{\lambda}}$	$\frac{-.93}{(0)}$ (-.12) [.91;4.81]	$\frac{1.53}{(0)}$ (-.13) [.58;5.07]	$\frac{5.60}{(0)}$ (.17) [.77;4.44]
$N^{\theta}_{\dot{\lambda}}$	$\frac{.348}{(0)}$ (-.36)(1.06)	$\frac{.39}{(0)}$ (-.33)(.90)	$\frac{.30}{(0)}$ (-1.35)(.66)
LATERAL-DIRECTIONAL			
$\Delta(s)$	(.16)(1.70)(2.48) [.30;2.20]	(.49) [.31;2.44] [.96;1.63]	(.52) [.30;2.66] [.74;1.41]
$N^{v}_{\delta_{as}}$	1.45(22.19) [1.0;1.96]	-12.2(-4.1)(1.83)(.062)	5.14(14.71)(.11)(.75)
$N^{\phi}_{\delta_{as}}$	.97(1.83)(2.16)(.060)	.928(.73) [.89;1.48]	.967(.55) [.51;1.61]
$N^{\psi}_{\delta_{as}}$	.104(.92) [-.49;.94]	$\frac{.126}{(0)}$ (.50)(1.95) [-.46;1.90]	$\frac{.165}{(0)}$ (.50)(.82) [-.14;1.91]
$N^{v}_{\delta_{rp}}$	$\frac{(1)}{(0)}$ { -1.04(-.59)(-10.6)(0) }	-28.67(.50) [.60;2.31]	-24.4(.50) [.56;2.19]
$N^{\phi}_{\delta_{rp}}$	$\frac{(1)}{(0)}$ { .433(0) [.43;.27] }	-.273(1.66)(-2.42)(.50)	-.186(.50)(1.76)(-2.41)
$N^{\psi}_{\delta_{rp}}$	$\frac{(1)}{(0)}$ { 1.05(.16) [.29;2.22] }	$\frac{.273}{(0)}$ (.50)(.51) [.49;2.30]	$\frac{.106}{(0)}$ (.50)(.43) [.57;2.80]

TABLE I-4

ELECTRONIC DISPLAY SYMBOL SENSITIVITIES*

DISPLAY FORMAT	ATTITUDE	POSITION		VELOCITY		CONTROL DIRECTORS
		VERTICAL	HORIZONTAL	VERTICAL	HORIZONTAL	
ED-1	Artificial horizon and fixed indices (10° increments); one-to-one with real world. Tail of A/C symbol: one-to-one with real world.	Altitude error diamond and fixed indices (50 ft increments): .015 cm/ft ±1.5 cm full scale Landing pad symbol: Diameter = 1 cm @ 875 ft AGL Diameter = 2 cm @ 100 ft AGL	Fixed A/C symbol and moving landing pad/approach course symbol: $\frac{6}{600+\hat{X}_e}\left(\frac{cm}{ft}\right)$ where $\hat{X}_e$ = range (ft)	None	None	None
ED-2	Same	Same	Same	Altitude rate error circle: $.15\ \frac{cm}{ft/sec}$ @ $\lambda = 90°$ $.03\ \frac{cm}{ft/sec}$ @ $\lambda = 0°$ ±1.5 cm full scale	Velocity vector/ velocity command diamond: $.0296\ \frac{cm}{ft/sec}$ (approach mode) $.118\ \frac{cm}{ft/sec}$ (Hover mode) Velocity error circle: $.02\ \frac{cm}{ft/sec}$ ±1 cm full scale	None
ED-2+	Same	Same	Same	None	Same	VTAB: ±1.5 cm full scale
ED-3	Same	Same	Same	None	Same as ED-2 with no velocity command diamond	HBAR } ±1 cm VBAR } full scale VTAB ±1.5 cm full scale

*A symbol deflection of 1 cm is equivalent to 0.85 degree of arc at the pilot's eye.

TABLE I-5

CONTROL DIRECTOR LOGIC

		FULL SCALE SIGNAL				
DIRECTOR ELEMENT	VARIABLE	RATE AUGMENTATION	ATT/RATE AUGMENTATION	ATTITUDE AUGMENTATION	AUTO λ	DECOUPLED VELOCITY CONTROL
HBAR	$\epsilon_{\dot{x}_h}$	$\pm$ 33 (ft/sec)	33	33	33	33
	θ_{wo}	$\pm$ 37 (deg)	75	75	75	--
	q	$\pm$130 (deg/sec)	230	230	230	--
VBAR	$\epsilon_{\dot{y}_h}$	$\pm$ 42 (ft/sec)	42	42	42	42
	ϕ	$\pm$ 20 (deg)	20	110	110	110
	p	$\pm$ 67 (deg/sec)	38	296	296	296
VTAB	ϵ_z	$\pm$100 (ft)	100	100	100	100
	$\epsilon_{\dot{z}}$ (λ = 0)	$\pm$ 50 (ft/sec)	50	50	50	250
	↓	↓	↓	↓	↓	↓
	(λ = 90°)	$\pm$ 10 (ft/sec)	10	10	10	50

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GLOSSARY OF SYMBOLS AND ABBREVIATIONS

Symbol	
a_X, a_Y, a_Z	acceleration along body X, Y, Z axis, respectively (ft/sec^2)
a_{ij}, a_{ij}	design parameters for decoupled velocity control system (Section V)
c	number of columns
d	displayed position (cm)
F	equations-of-motion characteristic matrix (1/sec)
F_{ES}	pitch stick force gradient (lb/in.)
g	acceleration due to gravity (32.2 ft/sec^2)
G	equations-of-motion control matrix
G_2	partitioned control matrix (Section V)
h	altitude (ft)
HBAR	horizontal bar control director deflection (volts)
$I_{(\;)}$	moment of inertia about body ( )-axis (ft-lb/sec^2)
I_{XZ}	product of inertia in body axes (ft-lb/sec^2)
J	control gain matrix (Section V)
J_2	partitioned control gain matrix
K	linear gain state feedback gain matrix (Section V)
$K_{(\;)}$	control director gain (volts/( ))
K_d	display position constant (cm)
K_L	non-dimensional inertia coupling in roll $\left(= \frac{I_Y - I_Z}{I_X}\right)$
K_N	non-dimensional inertia coupling in yaw $\left(= \frac{I_X - I_Y}{I_Z}\right)$
K_v	v-measurement calibration factor
K_α	α-measurement calibration factor
K_r	lateral guidance gain (deg/ft)
K_1, K_2	complementary filter gains (Section 4.2)
K_1, K_2, K_3	guidance gains (Section 4.3.3)
l_{X_n}	length from aircraft center-of-gravity to α-vane (ft)
l_{X_t}	length from aircraft center-of-gravity to tail LORAS (ft)
l_{Z_t}	height from aircraft center-of-gravity to tail LORAS (ft)
L	aerodynamic moment about body X-axis (ft-lb)

Symbol	
$L'_{(\ )}$	dimensional rolling moment derivative $= \frac{1}{I_X}\left(1 - I_{XZ}^2 / I_X I_Z\right)^{-1}\left[\frac{\partial L}{\partial(\ )} + \frac{I_{XZ}}{I_Z}\frac{\partial N}{\partial(\ )}\right]\left(\frac{\text{rad/sec}^2}{(\ )}\right)$
M	aerodynamic moment about body Y-axis (ft-lb)
$M_{(\ )}$	dimensional pitching moment derivative $= \frac{1}{I_Y}\frac{\partial M}{\partial(\ )}\left(\frac{\text{rad/sec}^2}{(\ )}\right)$
n_y, n_z	acceleration along body X and Y axes, respectively (g's)
N	aerodynamic moment about body Z-axis (ft-lb)
$N'_{(\ )}$	dimensional yawing moment derivative $= \frac{1}{I_Z}\left(1 - I_{XZ}^2/I_X I_Z\right)^{-1}\left[\frac{\partial N}{\partial(\ )} + \frac{I_{XZ}}{I_X}\frac{\partial L}{\partial(\ )}\right]\left(\frac{\text{rad/sec}^2}{(\ )}\right)$
N_j^i	numerator of the i/j (s) transfer function
p	body axis roll rate (deg/sec, rad/sec)
P	steady-state augmented control gain matrix (Section V)
q	body axis pitch rate (deg/sec, rad/sec)
Q	optimal control state weighting matrix (Section V)
r	body axis yaw rate (deg/sec, rad/sec)
r	number of rows (Appendix VI)
R	optimal control weighting matrix (Section V)
$\dot{R}_a$	angular rate of line of sight (rad/sec)
s	Laplace operator $\sigma \pm j\omega$
s	sample standard deviation
t	time (sec)
T_1	control director numerator zero (sec)
u	velocity along body X-axis (ft/sec)
u_L	velocity along body X-axis measured by u-LORAS (ft/sec)
u_2	partitioned control vector (Section V)
v	velocity along body Y-axis (ft/sec)
v_L	velocity along body Y-axis measured by v-LORAS (ft/sec)
V	velocity (ft/sec, kt)
V_e	horizontal inertial velocity vector (ft/sec)
V_W	horizontal wind velocity vector (ft/sec)

GLOSSARY OF SYMBOLS AND ABBREVIATIONS (Cont.)

Symbol	
$V_{W_{(\ )}}$	wind velocity component in ( ) direction (ft/sec)
$V_{X_a}, V_{Y_a}, V_{Z_a}$	earth-referenced velocity components with respect to the air mass (ft/sec)
VBAR	vertical bar control director deflection (volts)
VTAB	vertical tab control director deflection (volts)
w	velocity along body Z -axis (ft/sec)
X, Y, Z	generalized position coordinates (ft)
$X_{(\ )}, Y_{(\ )}, Z_{(\ )}$	dimensional longitudinal, lateral, and vertical force derivatives $= \frac{1}{M} \frac{\partial X, Y, \text{or } Z}{\partial (\ )} \left(\frac{\text{ft/sec}^2}{(\ )}\right)$
x	position (Section VI) (ft)
$\bar{x}$	sample mean
Y_{ijk}	generalized performance/workload measure
z_Y	height of accelerometer package above aircraft center of gravity (ft)
α	angle of attack (deg,rad) level of significance (Section X)
β	angle of sideslip (deg,rad)
γ	flight path angle (deg)
γ_{ij}	additive interactive effect
Γ	course (deg)
$\delta_{(\ )}$	evaluation pilot's controller position as - lateral stick (in.), positive right rp - rudder pedal (in.), positive right es - longitudinal stick (in.), positive aft cs - collective stick (deg), positive up λ - duct angle (ON-OFF)
$\delta'_{(\ )}$	$\delta_{(\ )}$ including control crossfeeds (Figure 5-5a)
$\Delta(\ )$	perturbation term $(\ )-(\ )_0$, units of $(\ )$
$\Delta(s)$	characteristic equation

GLOSSARY OF SYMBOLS AND ABBREVIATIONS (Cont.)

Symbol	
$\Delta_{(\ )}$	safety pilot's controller position as - lateral stick (in.), positive right rp - rudder pedal (in.), positive right es - longitudinal stick (in.), positive aft cs - collective stick (deg), positive up
$\epsilon(\ )$	error term = $(\ )_c$ - ( ), units of ( )
ϵ_{ijk}	additive random error in performance/workload model
ζ	damping ratio
ζ_θ	damping ratio of pitch attitude command prefilter
ζ_ϕ	damping ratio of numerator roots in ϕ/δ_{as} transfer function
ζ_d	damping ratio of Dutch roll characteristic roots
θ	pitch attitude (deg,rad)
θ_j	additive column effect in performance/workload model
K	display position constant (ft)
λ	X-22A duct angle measured from horizontal (deg)
μ	mean value
$\mu_{(\ )}$	mean value of ( ), units of ( )
σ	{standard deviation {real portion of Laplace operator
$\sigma_{(\ )}$	standard deviation of ( ), units of ( )
σ_x, $\sigma_{\ddot{x}}$	radar and accelerometer noise standard deviations, respectively (ft and ft/sec^2, respectively)
τ	generalized time constant (sec)
τ_{ij}	additive row effect in performance/workload model
τ_R	roll mode time constant (sec)
τ_S	spiral mode time constant (sec)
ϕ	roll angle (deg, rad)
ψ	heading angle $\triangleq \psi_N - \psi_A$ (deg)
ψ_A	approach course heading with respect to North (deg)
ψ_N	aircraft heading with respect to North (deg)
ω	{generalized angular frequency {imaginary portion of Laplace operator (rad/sec)

GLOSSARY OF SYMBOLS AND ABBREVIATIONS (Cont.)

Symbol

ω_n	undamped natural frequency (rad/sec)
ω_d	undamped natural frequency of Dutch roll mode (rad/sec)
ω_θ	undamped natural frequency of pitch attitude command prefilter (rad/sec)
ω_ϕ	undamped natural frequency of numerator roots in ϕ / δ_{as} transfer function (rad/sec)
ω_2	partitioned control vector (Section V)
$(\dot{\ })$	time rate of change of ( ), ( )/sec
$(\hat{\ })$	estimate of ( ), units of ( )
$(\ )^T$	transpose of matrix ( )
$(\ )_{AS}, (\ )_{BS}$	"after-switching" and "before switching" values of ( ) respectively, units of ( )
$(\ )_b$	aircraft body axis (Figure 4-2)
$(\ )_c$	commanded value of ( ), units of ( )
$(\ )_D$	design value of matrix ( ) (Section V)
$(\ )_e$	approach-course up (or "earth") axis (Figure 4-2)
$(\ )_F$	feedback signals for decoupled velocity control (Figure 5-5a)
$(\ )_h$	heading-up axis (Figure 4-2)
$(\ )_m$	measured value of ( ), units of ( )
$(\ )_{MAX}$	maximum value of quantity $\mu_{(\ )} \pm 2\sigma_{(\ )}$, units of ( )
$\|(\ )\|_Q^2$	$= (\ )^T Q (\ )$
$(\ )_{WO}$	washed-out value of ( ), units of ( )
$(\ )_o$	initial or trim value of ( ), units of ( )

Abbreviation

A/C	aircraft
ADI	attitude/director indicator
AGARD	Advisory Group for Aerospace Research and Development
AGL	above ground level
ANOVA	analysis of variance
A/S	airspeed
ATC	automatic turn coordination
CRT	cathode ray tube

GLOSSARY OF SYMBOLS AND ABBREVIATIONS (Cont.)

Abbreviation	
CTOL	conventional take-off and landing
CW	crosswind
DAC	digital-to-analog converter
dB	decibel
deg	degrees
DME	distance measuring equipment
ED	electronic display
F-( )	flight number ( )
FFCS	Feedforward Flight Control System
fpm	feet per minute
ft	feet
G/S	ground speed
GM	gain margin in decibels
H_a, H_0	alternate and null hypothesis, respectively
HH	heading hold
Hz	Hertz
IAS	indicated airspeed
ICL	Instrumentation and Control Laboratory
IFR	Instrument Flight Rules
ILS	Instrument Landing System
in	inches
ITED	Integrated Trajectory Error Display
ITVIC	Independent Thrust Vector Inclination Command
IVSI	Instantaneous Vertical Speed Indicator
JANAIR	Joint Army-Navy Aircraft Instrumentation Research
K	Thousands
KIAS	knots indicated airspeed
Kt	Knots
KW	Kilowatts
LORAS	Linear Omnidirectional Resolving Airspeed System

GLOSSARY OF SYMBOLS AND ABBREVIATIONS (Cont.)

Abbreviation	
MLS	Microwave Landing System
MS( )	mean square: E-error R-row C-column I-interaction
N/A	Not applicable
NI	no ITVIC
NASA	National Aeronautics and Space Administration
P	primary
PCM	pulse code modulation
PR	Cooper-Harper pilot rating
PI	performance index
PM	phase margin in degrees
rad	radian
RAE	Royal Aircraft Establishment
RMI	Remote Magnetic Indicator
RMS	root mean square
SAS	stability augmentation system
sec	second
SS ( )	sum of the squares: E-error R-row C-column I-interaction
STOL	short takeoff and landing
TAGS	Tactical Aircraft Guidance System
TER	turbulence effect rating
TIU	test input unit
VALT	VTOL Approach and Landing Technology
VBAR	vertical bar control director
VFR	Visual Flight Rules
VHF	Very High Frequency
VSS	variable stability system
V/STOL	vertical/short takeoff and landing
VTAB	vertical tab control director
VTOL	vertical takeoff and landing

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VTOL Flight Test
VTOL Stability and Control Augmentation Systems

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The third flight research program using the variable stability X-22A aircraft was undertaken to investigate control, display, and guidance requirements for VTOL instrument transitions. The primary purpose of the experiment was to provide meaningful data related to the interaction of aircraft control system and displayed information characteristics on pilot rating and performance during a steep decelerating descending transition from a representative forward velocity (100 Kt) to the hover completely under instrument conditions. Thirty-eight in-flight evaluations were performed of combinations of five

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generic display presentations, ranging from position-information-only to four-axis control directors, and five levels of control augmentation systems, ranging from rate-augmentation-only to decoupled longitudinal and vertical velocity responses and automatic configuration changes. In addition, new guidance developments of fundamental importance to VTOL instrument terminal area operations, including an Independent Thrust Vector Inclination Command (ITVIC) and a procedure for automatically switching between airspeed and ground speed tracking to account for headwinds and crosswinds, were conceived, designed, and demonstrated during the experiment. Primary results of the program include the demonstration of an inverse relationship between control complexity and display sophistication, as was hypothesized in the experiment design, and the definition of acceptable and satisfactory control/display combinations. In particular, it was found that the explicit display of translational velocities is required for a satisfactory system, regardless of control system complexity or automation, and that rate-augmentation-only may be acceptable (though still unsatisfactory) only if full control director commands are provided in addition to velocity status information. Analysis of the results in terms of simple pilot-in-the-loop considerations and measured performance and workload provide initial guidelines for the design of future VTOL control-display characteristics.